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LIGHT, PHOTOMETRY AND ILLUMINATING ENGINEERING

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LIGHT, PHOTOMETRY
AND
ILLUMINATING ENGINEERING

BY

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University of Maine

SECOND EDITION
SIXTH IMPRESSION

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PREFACE TO THE SECOND EDITION

This revision of the text is the result of years of experience in teaching illuminating engineering in the undergraduate curriculum. It has been the aim to make a satisfactory text for student use and at the same time to assemble material and information that will make the volume of value as a reference book for the practicing illuminating engineer and architect. The development of new illuminants and new equipment and progress in the art of illumination have made an extensive revision necessary. About two-thirds of the material is new. Eight chapters as chapters have been omitted. Some of the chapters of the old edition were combined and condensed, others were completely revised, and chapters of new material were added. The chapters on the Sources of Light, Principles of Interior Lighting, Illumination Calculations and Design, Interior Lighting Practice, and Principles of Street and Highway Lighting have been extensively revised. The chapters entitled Gas and Vapor Lamps, Modern Lighting, Lighting for Recreations and Sports, and Lighting the Highways and Airways are new.

Gas and vapor lamps are offering new and radical possibilities in lighting. Built-in lighting is producing more pleasing effects and higher class illumination than was previously thought possible. The improvements in street and highway lighting have reduced accidents and property damage where the new lighting systems have been installed. Progress in these fields and many others are discussed.

Much of the new material has been published in the *Transactions* of the Illuminating Engineering Society, the *American Architect*, the *Magazine of Light* and the publications of the General Electric Company. The author wishes to acknowledge the valuable contributions to the literature of illuminating engineering by L. J. Buttolph, P. S. Millar, T. S. Rogers, A. L. Powell, G. H. Stickney, Ward Harrison, C. E. Weitz, K. M. Reid, H. J. Chanon and others referred to throughout the book.

W. E. Barrows.

University of Maine, Orono, Me.,
January, 1938.

PREFACE TO THE FIRST EDITION

This book has been designed as a text in illuminating engineering and a reference work for the practicing engineer. It is an outgrowth of the author's previous books, *Electrical Illuminating Engineering* and *Light, Photometry and Illumination.* Approximately two-thirds of the present text is new; specifically, Chapters X and XII to XIX are entirely new and Chapters IX and XI partly so.

In choosing this material it has been the aim of the author to assemble the best ideas and thoughts available on the subject of artificial illumination and the choice of lighting equipment. In doing so the author has consulted freely the technical press, particularly the *Transactions* of the Illuminating Engineering Society and the *Bulletins* of the Edison Lamp Company, and has drawn freely from the writings of illuminating engineers and experts who are authorities in their branches of the subject. The author wishes especially to acknowledge the excellent articles by H. E. Ives, M. Luckeish, E. B. Rosa, P. S. Millar, G. H. Stickney, A. L. Powell, Ward Harrison, A. S. Turner, A. B. Oday, H. E. Butler, J. H. Kurlander, A. E. Anderson, S. L. E. Rose, H. A. Smith, E. Parker, R. E. Harrington, R. W. Peden, W. H. Rademacher, J. R. Covelle, R. E. Greiner and H. Schroeder.

Much information on present practice will be found in the chapters on the different classes of lighting. These can be studied with reference to the fundamental principles taken up in the preceding chapters and form the basis for constructive criticism and progressive thought in the classroom. It will be noted that various types of lighting installations are discussed. It has been the aim to choose those types which illustrate certain classes of lighting and will assist the student in arriving at a rational solution of illuminating engineering problems.

W. E. Barrows.

University of Maine, Orono, Me.,
August, 1925.

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LIGHT, PHOTOMETRY
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CHAPTER I

LIGHT AND VISION

Light is that form of radiant energy which is capable of producing vision. It is inherently the same as radiant heat, but of different frequency of vibration and wave length. The wave lengths for visible light cover but a small part of the radiant spectrum, as can be seen in Fig. 1-1. This illustration will also serve to remind us of the periodicity of many of the spectra which have become parts of everyday life.

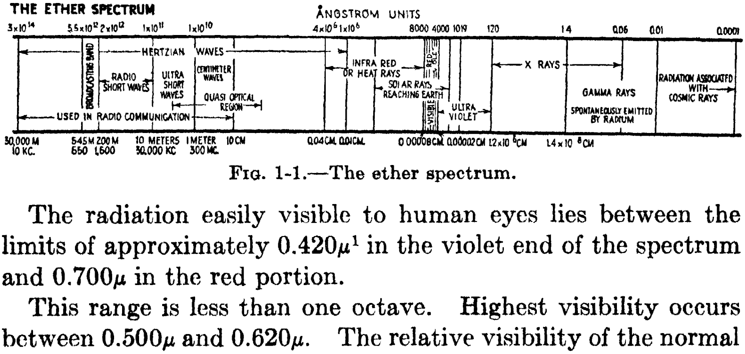


Fig. 1-1.—The ether spectrum.

The radiation easily visible to human eyes lies between the limits of approximately 0.420μ[1] in the violet end of the spectrum and 0.700μ in the red portion.

This range is less than one octave. Highest visibility occurs between 0.500μ and 0.620μ. The relative visibility of the normal eye to radiation from different parts of the visible spectrum is shown in Fig. 1-2. This visibility curve expresses the relation between light and energy throughout the visible spectrum, the visibility of energy being a maximum in the yellow-green (556μ).

[1] μ is the symbol used for the micron, which equals 0.001 mm. or 0.000001 m. The angstrom is also used with reference to wave length. It is equal to 0.0001 micron. Thus 1 m. = 1 million microns = 1,000 million millimicrons = 10,000 million angstroms.

At low intensities involving rod vision the visibility curve appears to be of similar shape but removed to the left and having its maximum value at 0.507μ.

At frequencies lower or at wave lengths greater than those of red light the energy radiated is known as the infrared or ultrared radiation; also at wave lengths shorter than those of the violet light the radiation is again invisible and is known as the ultraviolet radiation.

The visibility curves of any two observers may differ notably in relative values through the spectrum. Therefore, the relative intensities of two lights of different relative spectral-energy distributions, when measured even by the relatively accurate method of flicker photometry, may differ in value when compared by different observers.

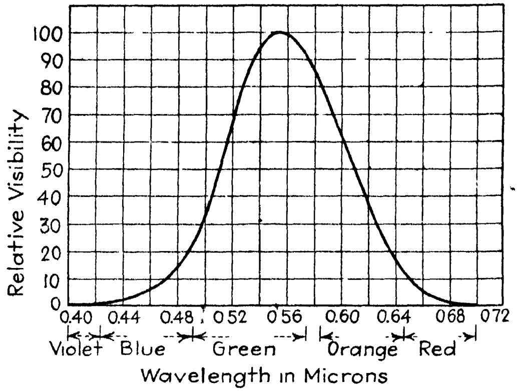


FIG. 1-2.—Spectral-luminosity curve of the average eye for a source of uniform energy-intensity.

This difference in spectral visibility among individuals is of such importance in photometry that a standard set of visibility data[1] representative of a normal observer (average of 200 individuals) was recommended by the International Commission on Illumination in 1924 and has been in use since then. Only by reference to some such defining set of data is it possible to define the luminous intensities of two lights of different chromaticity or the luminous reflectance of a chromatic surface. These relative visibility values are given in Table 1-1. Maximum visibility occurring at 0.556μ is taken as 100 per cent.

---

[1] *Bur. Standards Sci. Paper*, 475, 1923.

TABLE 1-1.—RELATIVE VISIBILITY OF RADIATION FOR AVERAGE NORMAL EYE

Wave length, μ	Relative to visibility at 0.556μ	Wave length, μ	Relative to visibility at 0.556μ
.400	0.0004	.600	0.631
10	0.0012	10	0.503
20	0.0040	20	0.381
30	0.0116	30	0.265
40	0.023	40	0.175
.450	0.038	.650	0.107
60	0.060	60	0.061
70	0.091	70	0.032
80	0.139	80	0.017
90	0.208	90	0.0082
.500	0.323	.700	0.0041
10	0.503	10	0.0021
20	0.710	20	0.00105
30	0.862	80	0.00052
40	0.954	40	0.00025
.550	0.995	.750	0.00012
60	0.995	60	0.00006
70	0.952		
80	0.870		
90	0.757		

Since the velocity of light of all colors is the same, or 3×10^{11} mm. per second (186,000 miles per second), it follows that the frequency of the light in different parts of the spectrum varies inversely as the wave length of the corresponding wave. Thus if the wave length of light producing highest sensibility is $0.556\mu = 556 \times 10^{-6}$ mm. its periodicity will be

$$f = \frac{V}{\lambda} = \frac{3 \times 10^{11}}{5.56 \times 10^{-4}} = 5.4 \times 10^{14} \text{ cycles per second} \qquad (1\text{-}1)$$

The frequency and wave length of some of the familiar forms of energy, reduced to practical units, are given in Table 1-2.

Spectral Energy of Light Sources.—The spectral-energy distribution in the visible region for sunlight, skylight, and light from incandescent lamps is shown in Fig. 1-3. It will be seen that much of the visible radiation of our light sources is of low

TABLE 1-2.—FREQUENCY AND WAVE LENGTH OF ENERGY

Form of energy	Cycles per second	Wave length in air
Alternating-current field	15	12,500 miles
Alternating-current field	25	7,500 miles
Alternating-current field	60	3,100 miles
Alternating-current field	125	1,500 miles
Wireless telegraph wave	10^5 to 10^7	10,000 to 100 ft.
Herzian waves	10^7 to 10^9	100 to 1 ft.
Infrared rays	6×10^{11} to 4×10^{14}	0.2 to 0.00003 in.
Visible light	4×10^{14} to 7.7×10^{14}	0.00003 to 0.000015 in.
Ultraviolet light	7.7×10^{14} to 3×10^{15}	0.000015 to 0.000004 in.
Lowest audible sound wave	15	66 ft.
Highest audible sound wave	8,000	1.5 in.

visual value. Even sunlight, in which the human eye has developed through the ages, has but a small part of its radiation in the highly visible region. These curves represent merely the distribution of the radiation in the spectral region and, while they represent to a considerable extent the color values of the light, they give no clue as to the physiological effect upon the eye.

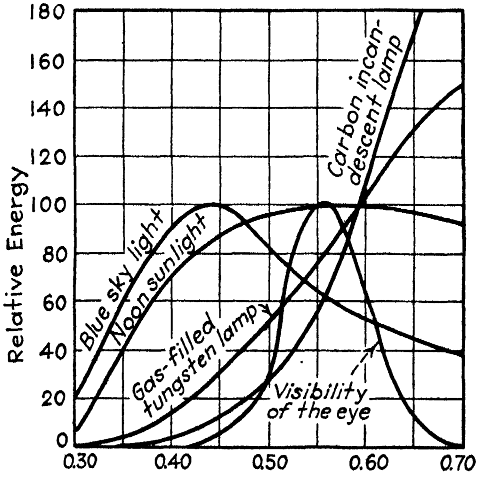


FIG. 1-3.—Spectral-energy-distribution curves for sources of light (qualitative only.)

In order to express *light in terms of radiation,* the visibility of the human eye for the same amount of radiant energy at each wave length of the visible spectrum and the variation of sensibility with intensity at constant wave length must be known.

Then spectral energy multiplied by the relative sensibility at each wave length is luminosity or objective light and the effect of this objective light upon the eye with respect to its variation of sensibility with intensity will give the subject light or visual sensation.

Luminosity Curves of Light.—In discussing the luminosity of a light source with respect to the quality or color of the light, a curve may be plotted showing the energy intensity of the source at various wave lengths. Then multiplying the ordinates of this curve by the sensitivity of the eye for each wave length and plotting the results will give what is known as the luminosity curve for the light. The area enclosed by the curve may be thought of as proportional to the total luminosity of the source

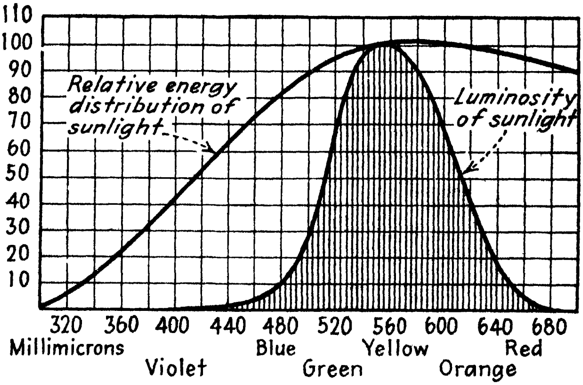


Fig. 1-4.—Relative energy and luminosity of sunlight.

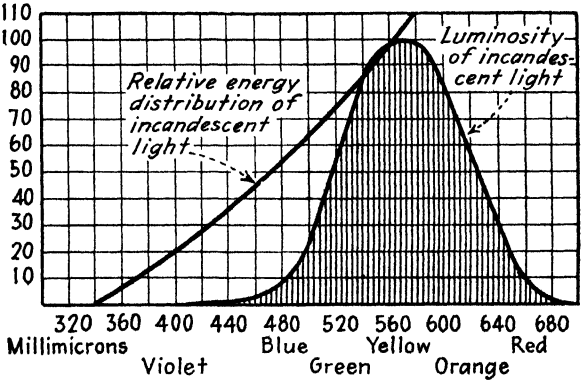


Fig. 1-5.—Relative energy and luminosity of incandescent light.

represented, while its shape and especially the position of the maximum indicates the color of the light as seen by the normal eye.

These curves are shown for sunlight in Fig. 1-4 and for incandescent light in Fig. 1-5.[1]

Luminous Radiation.—Luminous radiation may be produced by incandescence, luminescence, fluorescence and phosphorescence.

Incandescence, sometimes called temperature radiation or thermoluminescence, is the class of radiation due to the high temperature of the source, such as the incandescent-lamp filament, the Welsbach mantle of the gas lamp and the flames of the lamp and candle.

Radiation from incandescent sources usually gives a continuous spectrum in which energy of all wave lengths is present.

Luminescence or electroluminescence is produced by chemical or electrical action and nearly always occurs in gases or vapors. The luminosities of the gas and vapor lamps are examples of this phenomenon. The color of the light and the efficiency of the lamp become functions of the materials or gases involved rather than the temperature. The spectra of the luminescent sources are of the line or band type and characteristic of the gas or material used.

Fluorescence or photoluminescence refers to the property of a substance whereby energy absorbed at one wave length is radiated at another and usually longer wave length. For instance, when invisible radiations beyond the blue edge of the visible spectrum are impinged upon uranium glass a visible radiation is emitted.

Phosphorescence or chemiluminescence takes place when radiant energy is absorbed at one time and radiated later as a glow. There are luminous paints containing calcium sulphide which phosphoresce abundantly after exposure to visible radiation.

It is in luminescent sources that the highest luminous efficiencies of industrial significance are obtainable. In the flame and luminous arc lamps the light is due to the luminescence of the vapor stream. Its intensity is not a function of the temperature, but depends upon the chemical nature of the substances fed into the arc. In the mercury-vapor, neon, sodium and other types of gas and vapor lamps the color and the intensity of light are functions of the chemical composition of the gases which constitute the vapor stream and, while the intensity increases with increase in temperature, the variation is indefinite and in no way comparable with that of incandescent-light sources or a "black body."

---

[1] L. J. BUTTOLPH, *Trans. Illum. Eng. Soc.*, vol. 28, p. 153, 1933.

Black-body Radiation.—A body at any temperature other than absolute zero will radiate energy in all the wave lengths from zero upward; the wave length at which maximum radiation occurs depends on the temperature of the radiator. The amount of energy radiated varies according to certain laws which have been theoretically derived and experimentally verified. First, fundamentally, are the laws based on the principles laid down by Kirchhoff. Briefly these are

1. At any given constant temperature every body radiates the same amount of energy that it receives.
2. Black radiation must exist in every completely enclosed cavity whose walls are opaque and of the same temperature.

Black radiation may be defined as the radiation from a black body, and a *black body* as one which is not transparent, does not reflect, but absorbs, all incident radiation at all temperatures. It is obvious that the total energy radiated from such a body is greater than that from any other dissimilar body at the same temperature.

Probably the most general law is that known as the *Stefan-Boltzmann law of radiation.* Briefly, this law is that the total radiation from a black body is proportional to the fourth power of its absolute temperature, or

$$W = kT^4 = k(t + 273)^4 \qquad (1\text{-}2)$$

where T is the absolute temperature (degrees Kelvin) of the body, t is the temperature degrees centigrade, and k, the radiation constant, is approximately 5.71×10^{-12}.

From the above equation, then, the net radiation of energy from a black body to the surrounding air would be

$$W = 5.71 \times 10^{-12}(T^4 - T_0^4) \text{ watts per square centimeter} \qquad (1\text{-}3)$$

where T_0 is the absolute temperature of the surrounding air.

It will be seen that this law provides a means whereby a continuous *temperature scale* can be obtained from low to the very highest values of temperature since, by transposing,

$$T = \sqrt[4]{T_0^4 + \frac{W}{(5.71 \times 10^{-12})}} \tag{1-4}$$

where W is the radiation in watts per square centimeter, or

$$T = \sqrt[4]{T_0^4 + \frac{J}{(1.37 \times 10^{-12})}} \tag{1-5}$$

if J is the radiation in calories per square centimeter per second.

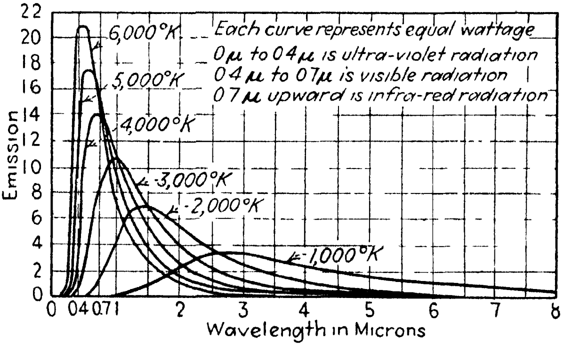


FIG. 1-6.—Black-body radiation.

Since the radiation of a body varies as the fourth power of its temperature, it is evident that the greatest efficiency of radiation will be obtained at the highest temperatures. Although the amount of visible radiation from a luminous source is a small part of the total radiation, it follows from the above that the efficiency of a source as an illuminant will vary greatly with the temperature. The relative values of the radiation at different wave lengths from black bodies at several temperatures are shown in Fig. 1-6. The total radiation is represented by the areas enclosed by the respective curves. Although the total area representing the radiation increases as the fourth power of the temperature in absolute degrees, it is evident that the rate of increase in visible radiation is still greater, due to the shifting of the maxima of the curves as indicated.

This increase in percentage of visible radiation continues to about 6500°K. to 7000°K. when the percentage of radiant energy in the visible spectrum is at a maximum or about 43 per cent and the emission is about 90 lumens per watt. At higher temperatures the percentage of energy radiated in the visible spectrum becomes less.

It is interesting to note that the above temperatures are approximately that of the sun and maximum radiation occurs at that part of the visible spectrum that offers greatest visibility to the human eye or 0.556μ.

Wien's Displacement Law.[1]—Wien's investigations brought out his displacement law bearing on the shift of the maxima of the radiation curves. The substance of this law is that the product of the wave length λ_m in microns, at which the energy radiation is maximum, and the absolute temperature T is equal to a constant a.

$$\lambda_m T = a = \text{constant} \tag{1-6}$$

where a is equal to about 2,960 for a black body and 2,630 for platinum.

Combining this law with that of Stefan and Boltzmann gives the relation for black bodies

$$W_m T^{-5} = b = \text{constant} \tag{1-7}$$

where W_m is the energy of radiation corresponding to the wave length of the maximum energy radiation λ_m and T is the absolute temperature.

For other than black bodies the law is complicated by the absorptive power of the body. For certain metals the relation is closely represented by the expression

$$W_m T^{-c} = \text{constant}$$

while for other metals this equation will in no way hold. For polished platinum c is equal to about 6.0.

Planck's Equation.—From the study of the radiation curves for a complete radiator Planck derived the empirical equation which for radiation in the visible region is

$$W = C_1 \lambda^{-5} \epsilon^{-\frac{C_2}{\lambda T}} \tag{1-8}$$

---

[1] *Trans. Illum. Eng. Soc.*, vol. 4, p. 67, 1909.

where W is the energy radiated in watts per square centimeter at wave length λ; $C_1 = 3.7 \times 10^4$; λ is the wave length in microns; $\epsilon = 2.718$; $C_2 = 14{,}350$; T is the absolute temperature in degrees Kelvin. Curves for several temperatures from 2000° to 10,000°K. and based on the above constants are shown in Fig. 1-7. Curves so derived approximate those for several illuminants. The curve for 2000°K. resembles closely that of the candle flame in the visible region. The gas-filled tungsten lamp of 2700° to 3200°K. approximates the 3000°K. curve. Average noon sunlight is approximated by the 5000°K. curve, average daylight by a 6500°K. curve, a blue sky by that for 10,000°K.

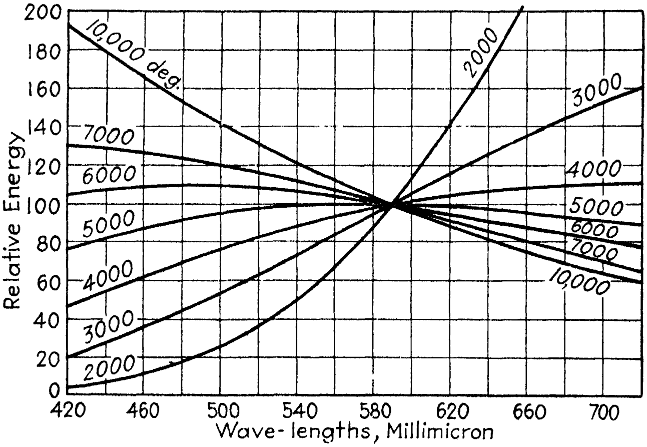


FIG. 1-7.—Spectral-energy distributions of the hypothetical Planckian radiator for 2000 to 10,000°K.

Selective Radiation.—A higher luminous efficiency may be obtained for the same temperature, however, by employing a radiator capable of selective radiation in the short wave lengths. A black body is a "complete radiator"; *i.e.*, it is said to radiate at any temperature a maximum amount of energy in every wave length. Such a body will be a complete absorber and will absorb all energy incident upon it. A body which is not a complete radiator will radiate less energy at each wave length than a black body at the same temperature. If the energy radiated in each wave length is reduced by a constant proportion, the ratio of the visible energy radiated to the total energy radiated will be the same as that of a black body, and the luminous efficiency will be the same as that of a black body at the same temperature. Such a body is termed a *gray body*, and, in place of absorbing all the energy falling upon it, it will reflect a certain percentage of each wave length. If a body radiates less energy than a black body at the same temperature but radiates a relatively larger proportion of energy at certain wave lengths than at others compared with a black body, it may be said to

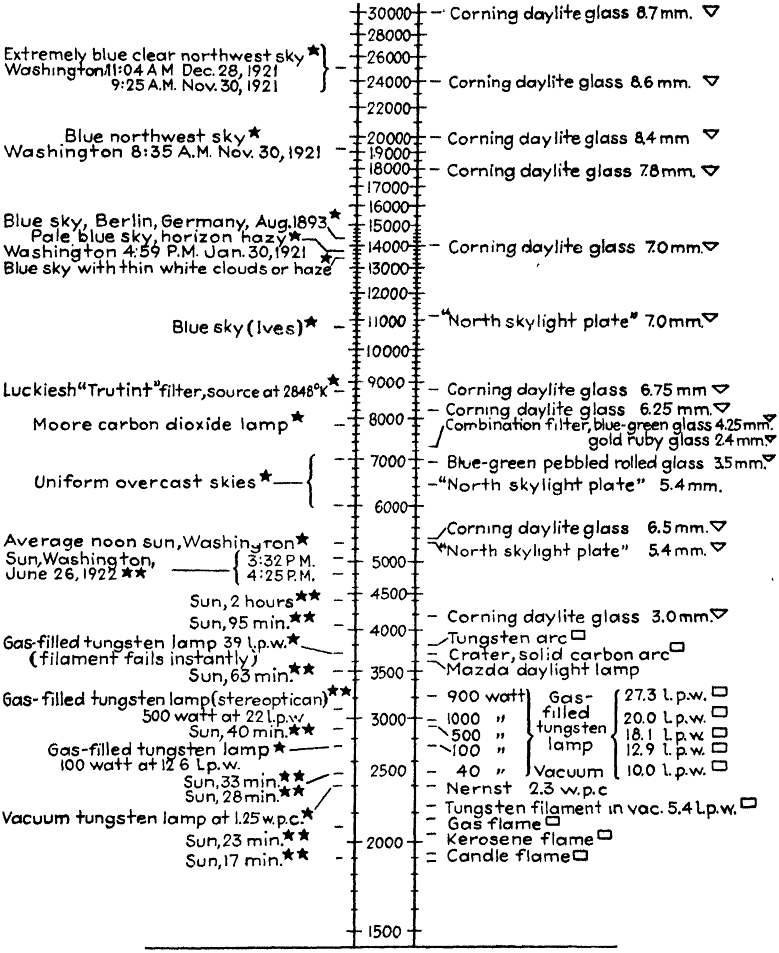
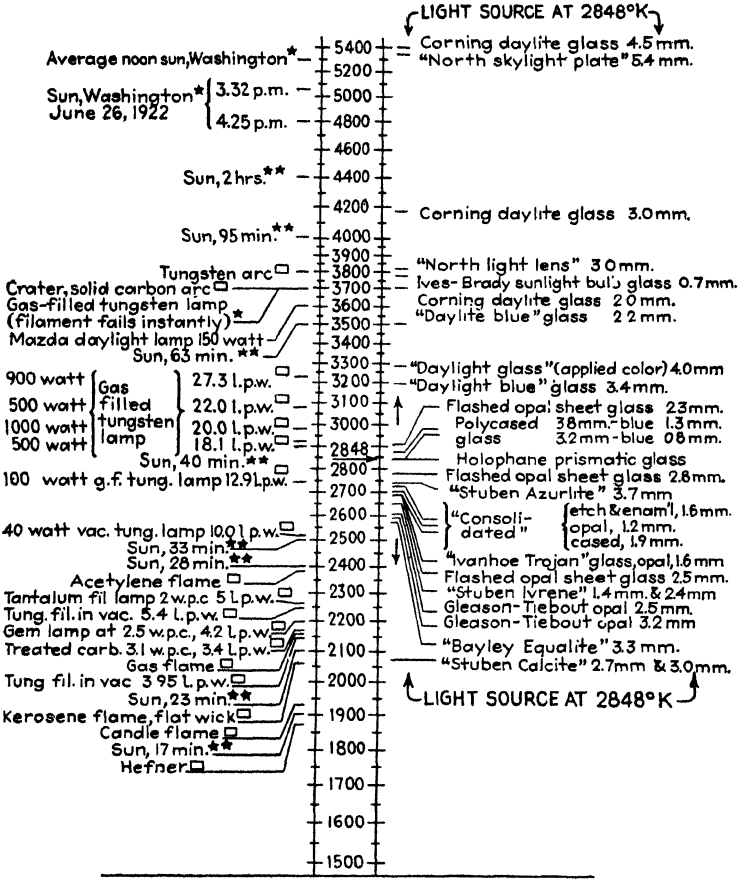


FIG. 1-8.—Daylight and artificial light on color-temperature scale. Daylight and sunlight from 1900 to 24,000°K. and artificial light below 4000°K. and as modified by filter glasses to 30,000°K. with a light source at 2848°K.

radiate selectively in the former wave lengths. Thus, if a body radiates selectively in the wave lengths of the visible region its luminous efficiency will be greater than that of a black body at


LIGHT SOURCE AT 2848°K
Average noon sun, Washington★
Sun, Washington★ June 26, 1922 3.32 p.m.
4.25 p.m.
Sun, 2 hrs.★★
Sun, 95 min.★★
Tungsten arc□
Crater, solid carbon arc□
Gas-filled tungsten lamp (filament fails instantly)★
Mazda daylight lamp 150 watt
Sun, 63 min. ★★
900 watt Gas filled tungsten lamp 27.3 l.p.w.□
500 watt 22.0 l.p.w.□
1000 watt 20.0 l.p.w.□
500 watt 18.1 l.p.w.□
Sun, 40 min.★★
100 watt g.f. tung. lamp 12.9 l.p.w.□
40 watt vac. tung. lamp 10.0 l p.w.□
Sun, 33 min.★★
Sun, 28 min.★★
Acetylene flame □
Tantalum fil lamp 2 w.p.c 5 l.p.w.□
Tung. fil. in vac. 5.4 l.p.w. □
Gem lamp at 2.5 w.p.c., 4.2 l.p.w.□
Treated carb. 3.1 w.p.c., 3.4 l.p.w.□
Gas flame □
Tung fil. in vac 3 95 l. p.w.□
Sun, 23 min.★★
Kerosene flame, flat wick□
Candle flame □
Sun, 17 min.★★
Hefner□
5400
5200
5000
4800
4600
4400
4200
4000
3900
3800
3700
3600
3500
3400
3300
3200
3100
3000
2848
2800
2700
2600
2500
2400
2300
2200
2100
2000
1900
1800
1700
1600
1500
Corning daylite glass 4.5 mm.
"North skylight plate" 5.4 mm.
Corning daylite glass 3.0 mm.
"North light lens" 3 0 mm.
Ives-Brady sunlight bulb glass 0.7 mm.
Corning daylite glass 2 0 mm.
"Daylite blue" glass 2 2 mm.
"Daylight glass" (applied color) 4.0 mm
"Daylight blue" glass 3.4 mm.
Flashed opal sheet glass 2.3 mm.
Polycased glass 3.8 mm.-blue 1.3 mm.
3.2 mm-blue 0.8 mm.
Holophane prismatic glass
Flashed opal sheet glass 2.8 mm.
"Stuben Azurlite" 3.7 mm
"Consolidated" etch & enam'l, 1.6 mm.
opal, 1.2 mm.
cased, 1.9 mm.
"Ivanhoe Trojan" glass, opal, 1.6 mm
Flashed opal sheet glass 2.5 mm.
"Stuben Ivrene" 1.4 mm. & 2.4 mm
Gleason-Tiebout opal 2.5 mm.
Gleason-Tiebout opal 3.2 mm
"Bayley Equalite" 3.3 mm.
"Stuben Calcite" 2.7 mm & 3.0 mm.
LIGHT SOURCE AT 2848°K

★★ Direct sunlight, time after sunrise and before sunset.
Data marked ★ and ★★, by Priest; □ by Cady and Dates.
▽, with light source 2848°K

FIG. 1-9.—Sunlight and artificial light on color-temperature scale. Sunlight range below 5400°K., artificial light from a light source at 2848°K. raised and lowered in color temperature by modifying glasses.

the same temperature. This fact accounts in part for the higher efficiency of some of the new types of incandescent lamps, although the principal cause of the higher efficiency is the higher temperature at which they operate.

It has been proposed that a method as indicated on the preceding pages and known as color temperature form the basis for classifying our artificial illuminants, sunlight and daylight.

Color Temperature.—The color temperature of a source of luminous radiant energy is the temperature at which a complete radiator (perfect black body) must be operated to give a color matching that of the source in question.

It is measured from the absolute zero in degrees of the centigrade scale, and to distinguish the absolute scale from the usual centigrade scale, it is designated as degrees Kelvin, *e.g.*, 3000°K.

The actual temperature of the source or body may not be at all comparable with its color temperature; *e.g.*, blue sky, which, of course, is actually very cold, may have a color temperature of 25,000°K.

A classification of light sources, natural and artificial, on the basis of color temperature is shown in Figs. 1-8 and 1-9.[1] There are also indicated the color properties of glassware used with a light source of 2848°K. color temperature. A study of these data, especially those relative to daylight and skylight values, is interesting. Reference will be made to these figures and data later in the text.

VISION

The Human Eye.—Visual sensibility to variations in luminous intensity decreases continually with increasing intensity. Compared with physical instruments, the eye has a most extraordinary range. It may be used with ease at intensities a million times the minimum perceptible intensity. This great power of accommodation is due chiefly to the decrease of sensibility with increase in intensity. The part which the eye plays in protecting itself against high intensities and adapting itself to low intensities can be best understood from a brief description of its construction.

The eye consists essentially of three parts—the *iris*, the *focusing lens*, and the *retina* (see Fig. 1-10). It resembles a camera in general structure and action. The *iris* is a diaphragm which expands or contracts to regulate, to a certain extent, the amount of light that, passing through the focusing lens, falls upon the retina at the rear of the eyeball. The *focusing* (crystal-

[1] PRIEST, *Trans. Illum. Eng. Soc.*, vol. 18, pp. 681, 865, 1923.
MACBETH, *ibid.*, vol. 23, p. 302, 1928.

line) *lens*, under the control of the ciliary muscles, is regulated so as to focus the images exactly upon the retina. The *retina* contains the optical nerves, which communicate with the brain. At the center of the retina is the region of greatest sensitiveness, known as the fovea. It is at this spot that vision is most acute and where the image is formed when the eye is directed at the object of vision. The impression formed on the remainder of the retina is used merely for orientation.

The peculiarities of the optical system with reference to different intensities of light have given rise to the theory of a double nerve system in the retina. These nerves are known as the rods and cones and have decidedly different sensibilities in respect both to intensity of light and to color of stimuli.

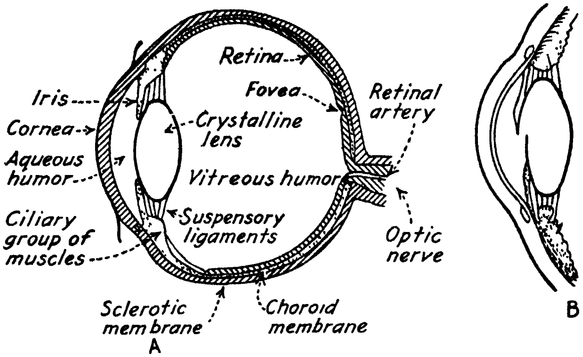


FIG. 1-10.—Cross section of the human eye.

The *cones* are supposed to be the form-receiving and color-perceiving elements of the retina; in other words, they are the visual cells.

The supposition is that the *rods* form the special apparatus for vision in dim light (night vision). They contain a pigment, known as visual purple, which is very sensitive to light. This visual purple is found only in the external segments of the rods; the cones do not contain it; therefore the fovea, which has only cones, does not contain it. It has been shown that a photograph may be made upon the surface of the retina by the bleaching of the visual purple where it is exposed to light. In the visual purple there is, therefore, an unstable substance readily decomposed by the mechanical or chemical effect of the ether waves. Some radiations are very much more active than others in bleaching this substance, greenish yellow being most active, yellow next, blue next, violet next, and red least active in this process.

Provision is made in the retina for the constant regeneration of the visual purple, the restoration process taking place rapidly in dim light or darkness. The external segments of the rods impinge upon a layer of heavily pigmented cells—the pigmentary layer mentioned above. When the eye is exposed to light, the black pigment of these cells migrates so as to be in position to restore the color to the bleached or used-up visual purple. Additional experiments on this subject have shown that the velocity of the bleaching of visual purple by light under comparable conditions of concentration, volume, and surface exposed is directly proportional to the intensity. The experiments also confirmed the Bunsen-Roscoe law, which states that, in order to produce a definite photochemical change in a given system, the product of the light intensity and the time of its action must be a constant. At low intensities, below 0.02 foot-candle, vision appears to be accomplished by the retinal rods alone, while vision at higher intensities brings into play the less sensitive but more efficient retinal cones. The two functions overlap widely, so that the transition from rod to cone vision is very gradual.

At intensities greater than 1 foot-candle the cones exert the predominating influence and show maximum sensibility to light of a yellowish-green hue, while at low intensities, where the rods only respond, the eye is most sensitive to light from the bluish-green part of the spectrum. Thus the eye accommodates itself to high or low intensities by closing or opening the iris and by employing sets of nerves of different sensibilities.

The human eye is not achromatic and is not corrected for chromatic aberration. Its dispersive power is slightly greater than that of water. It is known that for near vision the normal eye will generally focus itself for blue rays, while difficulty is experienced in attempting to focus the eye for red rays. The reverse is true for distant vision. While this is true for large and small distances of vision, differences in the ease of accommodation for red and blue rays become less marked for vision at intermediate distances. At a distance of $1\frac{1}{2}$ m., according to Luckiesh,[1] no noticeable difference in ease of accommodation for red and blue rays appeared to three observers who had experienced no abnormality in their power of accommodation.

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[1] M. Luckiesh, *Elec. World*, vol. 58, p. 1255, 1911.

As a person increases in age, the elasticity of the lens diminishes, thus reducing the accommodation of the eye. This change begins at an early age and continues through life. According to Godinez,[1] the amplitude of accommodation at different ages is as indicated in the following table:

TABLE 1-3.—ACCOMMODATION OF THE EYE

Age, Years	Amplitude of Accommodation, Diopters
10	14
15	12
20	10
30	7
40	4.5
50	2.5
60	1.0
75	0.0

Experimental data obtained by Cravath[2] show that the intensity of illumination required by individuals of different ages for good visibility is, in general, proportionally identified with the age of the individual, as might be inferred from the above table.

The unconsciousness of the great variations in the amount of natural light by which people see and the absence of annoyance or discomfort under even extreme cases merely corroborate the great range of adaptability and accommodation of the human eye.

Glare.—Glare may be defined as any brightness within the field of vision of such a character as to cause discomfort, annoyance, interference with vision, or eye fatigue. It is one of the most common and serious faults of lighting installations.

Glare is objectionable because, when continued, it tends to injure the eye and disturb the nervous system; it causes discomfort and fatigue and reduces the efficiency of the individual; it interferes with clear vision and thus reduces the efficiency and, in many cases, increases the risk of accident or injury to the worker.

There are five principal causes of glare:

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[1] GODINEZ, *Trans. Illum. Eng. Soc.*, vol. 6, p. 802, 1911.

[2] CRAVATH, *ibid.*, vol. 6, p. 793, 1911.

1. The light source may be too bright.
2. The candle power of the light source may be too great in the direction of the eye.
3. A given light source may be located too near the eye, or it may lie too near the center of the field of vision, for comfort.
4. The contrast between the light source and its darker surroundings may be too great.
5. The time of exposure may be too great, *i.e.*, the eye may be subjected to strain caused by a light source within the field of vision for too long a time.

The maximum intensity of light in the direct line of vision which the eye can endure without annoyance and possible harm is about 4 or 5 candles per square inch. The greater the brightness or the larger the area of the source the more will the eye be affected. Since all the modern light sources have an intrinsic brightness greater than the above values it is obvious that they should be surrounded with globes of diffusing material of such size and diffractiveness as to present an intensity not greater than 4 or 5 candles per square inch.

Seeing.—Seeing is the real purpose of lighting. This should be continually kept in mind. A salient feature of good lighting is the prevention or reduction of defective vision and unnecessary waste of human resources. It seeks to achieve this through the improvement of the conditions governing visibility.

The visibility of an object is influenced by the size and detail of the object, the level and quality of illumination, the contrast in brightness and color, and the time required or available for the observation. Also the visibility of an object depends upon the efficacy of the individual. Eye defects, fatigue optical and physical, and distraction affect this efficacy.

Eye fatigue which lowers the visual efficiency of the eye may be due to retinal fatigue and muscular fatigue. A glare source, either in front of or behind the object of attention, has a greater tiring effect than if in the plane of attention. The rotating and particularly the focusing muscles of the eyes tend to fix on the source of glare and it is the strain of keeping them adjusted to the object that produces much eye fatigue. The same fatigue effect can be quickly realized by reading a double impression made by the paper slipping during the printing process. The fatigue here is produced by the efforts of the lens muscles to focus on the two impressions.

A dilation of the pupil occurs as a result of a day's work involving visual effort. It has been found that relaxation afforded by a night of sleep only partially offsets this effect.[1] The effect of close visual work, as indicated by pupillary changes, gradually increases during the work week. Considerable recuperation takes place over the week end. However, the severity of close visual work emphasizes the need of establishing optimum conditions for seeing.

Statistical analyses have established the fact that the eyes become defective through age, use, and abuse. Although the eyes have the ability to compensate for severe or unnatural visual conditions, they are eventually injured in doing so. Recent scientific developments emphasize that differences in the size and location of the retinal images are responsible for certain aspects of defective vision. It is probable that such defects would be much less serious if vision were limited to easy and natural tasks. Also individuals having lower retinal sensibility have the larger natural pupil, and require higher illumination intensities to see clearly.

The ability of the eye to see an object depends upon at least four variables: size, contrast, brightness, and time of exposure. The results of investigations by Luckiesh[2] show that two visual tasks may be equally difficult when each of these factors differs, as indicated in Fig. 1-11. Size is measured in visual angle—minutes subtended by the object at the eye. Contrast is defined as the ratio of the brightness-difference between the object and its background to the brightness of the background and for simplicity is expressed as percentage of contrast. A perfectly black object on a perfectly white background has a contrast of 100 per cent. Brightness usually means the brightness of the background because the object to be seen is usually small and actually the background is a part of the thing seen. If the objects or details cover an appreciable part of the background, *e.g.*, a page of printed matter, the brightness is the average brightness.

The size of an object just visible depends upon all the factors of light and of lighting. Assuming every factor constant excepting intensity of illumination, the minimum size of an object just visible, or rather the minimum spacing between critical details which can just be resolved by the average normal eye at a distance of 14 in., is as follows:

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[1] M. Luckiesh and F. K. Moss, *ibid.*, vol. 29, p. 641, 1934.

[2] Luckiesh, *ibid.*, vol. 25, p. 15, 1930.

Foot-candles	1	10	100
Size of object in inches	0.00467	0.00357	0.00264
Relative size of object	100	76	57
Relative visual acuity	100	131	177

It is seen that approximately the same increase in visual acuity is obtained by increasing the level of illumination from 1 to 10 foot-candles as for an increase from 10 to 100 foot-candles. These results apply to borderline seeing at which seeing is only 50 per cent certain.

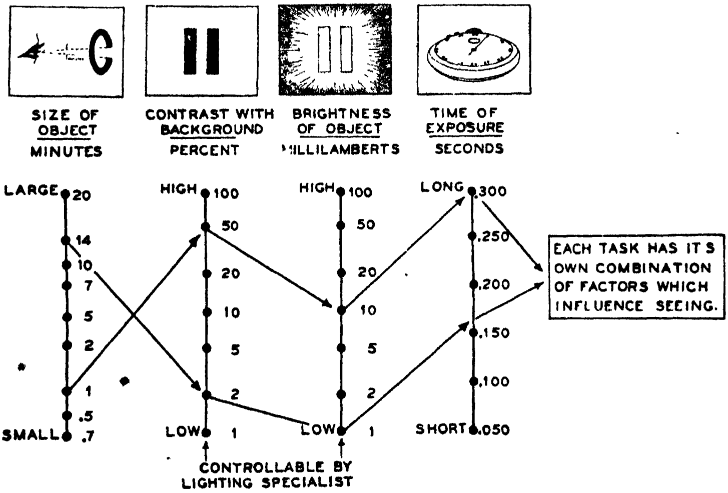

FIG. 1-11.—Factors which influence seeing.

Illumination and Discrimination.—Good vision requires more than the mere perception of an object; it requires the discrimination of its fine details as well. The speed with which this discrimination can be accomplished—or, in other words, the speed of vision—involves all factors of light and lighting which influence the ability of the eye to distinguish differences in brightness, color, and fine detail. Tests conducted on the relationship between the time required for discrimination and the intensity of illumination show the general trend indicated in the curves of Fig. 1-12. Thus the eye discriminates details more rapidly under the higher levels of illumination, although requiring more time than for mere perception.

In the astigmatic eye the time required for discrimination is even more dependent upon the level of illumination. These curves are confined to the range of illumination values in which the speed of discrimination changes most rapidly. Thus at the lower levels of illumination the astigmatic eye is handicapped to an even greater extent than the normal eye. Conversely, an increase in illumination benefits the astigmatic eye to a relatively greater extent than the normal eye. This fact is especially worthy of note because statistics have shown that more than half of the industrial workers of today have defective vision.

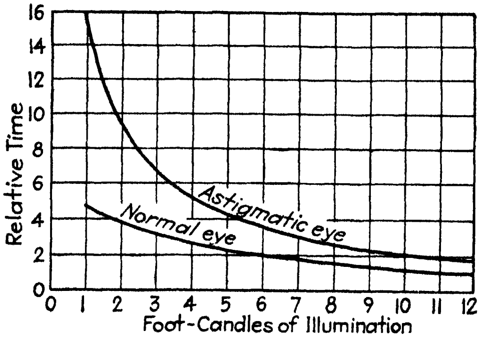

FIG. 1-12.—Time and light required for discrimination. Astigmatic and normal eyes.

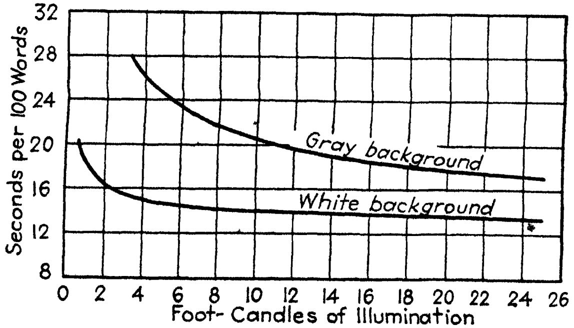

FIG. 1-13.—Time and light required for reading "Old English" type.

Brightness contrast is another factor which influences the speed of vision. Recent tests on the speed of reading involve both discrimination and brightness contrast in conditions similar to those encountered in office work and the like. Figure 1-13 contains the results of two such tests, which again demonstrate the fact that the speed of vision is lessened by inadequate illumination and that it also varies with the degree of contrast of an object with its background. This latter fact is significant, since in the everyday use of the eye, with the single exception of the printed page, brightness contrasts are seldom found so pronounced as black or white, which is the best condition for visual acuity.

Visual Acuity.—The ability to distinguish detail is closely associated with the brightness of the object viewed, the contrast of its details, and the character of the light entering the eye. There is a wide variation among individuals as to acuity of vision. In general, a high intensity of illumination is necessary for a high acuity; however, there is a limiting brightness above which there is no increase in acuity, the increase stopping at values of illumination well below those which produce glare. In general, acuity is better the greater the contrast. This contrast is greater in the case of white on black or light objects on a dark background than for black on white or dark objects on a light background. It is well known that an increase in size of object functions in some unknown relation as increase of brightness (irradiation).

Increase of intensity of light produces an important effect in decreasing the size of the pupil. This results in a clearer image with greater sharpness of detail. This effect is especially pronounced when there is a fault in the focusing action of the refractive system. It has been found that pupils 1.2 to 2 mm. in diameter render the eye practically independent of both errors of refraction and of changes in accommodation.

Thus in cases of presbyopia (failure of accommodation due to age) or presbyopic eyes (those needing the aid of convex lenses) a high intensity of illumination is of great service.

Visual Acuity and Monochromatic Light.—It appears that monochromatic light produces a more distinct retinal image and is better for distinguishing details than light of a normal spectrum. Some of the gaseous tubular sources such as the mercury and sodium lamps that emit band radiation approach monochromatic characteristics. The mercury-vapor lamp is well established in several classes of service where detail work of a trying nature is performed.

The combination of monochromatic lights, *e.g.*, red, yellow and blue, will give less acuity than the source of one alone. This is obvious because of the want of achromatism of the eye and can be explained by Fig. 1-14. Assuming the yellow rays to be brought to a focus on the retina, the blue rays will be brought to a focus in front of it and the red rays behind it. It is obvious then that, if the eye cannot focus itself for a certain color of light, no amount of that light will make the observer see distinctly, and since it cannot focus itself for two or more different colors, it will doubtless focus on the resultant color of the mixture, which will not be monochromatic and, consequently, will produce less acuity.

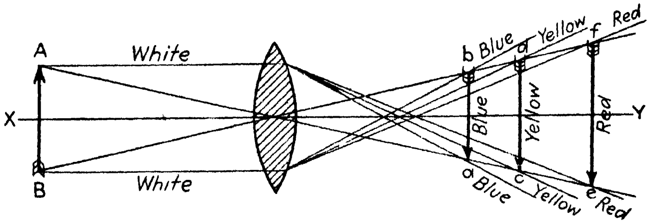

FIG. 1-14.—Principle of chromatic aberration.

Fechner's Law.—About 1830 Weber observed that the least perceptible increment to a stimulus affecting several of the sense organs, including the organs of vision, under fixed conditions of fatigue, attention, and expectation, bore a definite relation to the amount of that stimulus. Fechner later extended these investigations and formulated his results in the mathematical expression

$$\frac{dB}{B} = \text{constant} \qquad (1\text{-}9)$$

known as the "Fechner fraction," where B is the value of the stimulus and dB is the least perceptible increment.

Based on his investigations, Fechner formulated what has become known as Fechner's law which, stated briefly, is this: As the stimulus of the eye is increased in geometric progression the resulting sensation increases in arithmetic progression. This relation appears to hold over a wide range of intensities, failing only at low and very high values. Walsh[1] shows that the Fechner fraction is practically constant over a range of brightnesses from 30 to 10,000 photons, a photon being the illumination of the retina when the brightness of the object looked at is 1 candle per square meter and the aperture of the pupil is 1 sq. mm.

No empirical expression has yet been found to fit the contrast sensitivity curves of the eye. Especially is this so at low values of field brightness where the contrast sensitivity of the eye is reduced, and is much less for red light than for white or blue light.

Color Sensation.—There appears to be a lag in color sensation on both the presentation and cessation of the stimulus. Also the rate of rise and fall of color sensation is different for different colors. Of the three primary colors the response to green is the slowest and to blue the fastest. Color sensation persists as an afterimage for some little time after the stimulus is removed. It changes in appearance during decay. If the eye is subjected to moderate intensity of white light immediately at the cessation of the stimulus the afterimage due to the first stimulus will appear complementary in color to the first stimulus.

Simultaneous Contrast.—Colors mutually affect each other when viewed simultaneously, the effect being greatest when the colors are in juxtaposition. When red and green, for example, are viewed in juxtaposition the red appears redder and the green appears greener than if viewed separated or separately. Intensity contrast acts similarly and in conjunction with color contrast if color exists.

Purkinje Effect.—It appears that the normal eye is relatively more sensitive to and can distinguish details better in light of a bluish hue when the illumination is of low intensity while light of a greenish-yellow hue becomes more efficacious when cone vision comes into prominence and at higher illumination intensities. For instance, if a red and a blue appear of the same brightness under ordinary illumination the blue will appear much brighter when the intensity of illumination is low. The brightness at which the Purkinje effect begins to be noticeable depends upon several factors and conditions but appears to be, under ordinary conditions, approximately that of a white surface illuminated to 0.5 foot-candle.

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[1] J. W. T. Walsh, *Photometry*, p. 53, Archibald Constable & Company, Ltd., London, 1926.

Irradiation.—A bright object seen from some distance away appears larger than it really is. This phenomenon is characteristic of the functioning of the eye.

Psychological Effects and Optical Phenomena.—The impressions received of light and illumination are liable to be distorted by psychological influences. Habit is likely to influence the choice or preference of particular illuminant or a particular type of installation. Public comment and personal opinions may prejudice a person. The laws of association, suggestion, attention, and expectation should be understood by the student of illuminating engineering. Any or all of these psychological peculiarities may operate to the annoyance of the practicing engineer, or may be used by him to his advantage.

Since artificial light is used for observing objects, its effectiveness is judged from the impressions that it produces. The impression is usually the result of attention, stimulated perhaps by association, suggestion, or expectation. Attention will not attach itself firmly to uninteresting objects. It will decline if some change or some new attribute is not discovered in the object. Fatigue of the optical system results from the strain of continuous attention toward any one object, and the impression becomes less intense. This statement may easily be proved by continuing one's gaze intently upon one particular object. When attention to one object becomes exhausted, rest is obtained either by reflex attention or by directing the attention to other subjects.

Attention continuously centered upon the same subject or upon an unchanging object has been proved by experiment to tend toward either a hypnotic state or a comatose condition. Thus in the installation of illumination systems as well as in the disposal of the areas illuminated the arrangement should be such that there will be contrast in the intensity of illumination of the objects illuminated and in the intensity of the shadows produced.

A peculiar optical phenomenon occurs after looking at a brightly illuminated body, owing to fatigue of the eye. If, for instance, after looking intently for some time at a red surface the eyes turn to a white surface, it will appear greenish blue, or after looking through a green glass for a few moments white will appear a reddish white. Another peculiarity of the optical system is that if alternate strips of black and white are looked at closely the white will appear much whiter by contrast with the black, and a black body with a red background can be distinguished as to detail at a greater distance than if the background were green. Moreover as *illumination grows very bright* all colored objects incline toward a whitish-yellow tint, which must gradually modify the quality of the sensation appropriate to that particular color of light. A red surface appears brighter than a blue one in daylight, while the reverse occurs if these surfaces are viewed in weak daylight, when red may appear black while the blue will still be visible in its proper color. In a bright light red, orange and yellow surfaces are relatively more brightly illuminated than blue or violet surfaces, while just the opposite relations occur in a weak light.

Ultraviolet Radiation.—The many uses of ultraviolet radiation and the possibilities of further knowledge and more applications make the subject interesting. The purifying effects of the ultraviolet radiation of sunlight is universal knowledge. The effect of ultraviolet radiation on certain forms of bacteria is well known. The cure of rickets by radiation is a practice of the medical profession. In the treatment of colds, tuberculosis, and pernicious anemia it is believed to be beneficial.

According to present knowledge ultraviolet radiation should be considered as a toxic agent. Its effect is really to kill any living cell that absorbs it. It may be beneficial if taken in small quantities. Dangers lie in the indiscriminate use of radiation therapy. An overdose of sunburn is uncomfortable, dangerous, and sometimes fatal. Ultraviolet treatment in overdose causing erythema or sunburn of a considerable area of the skin is to be avoided in diseases of the heart and kidney.

The wave length 2967Å. is approximately the wave length of greatest effectiveness in producing erythema or sunburn and in the prevention and cure of rickets.

The rubescence curve is the spectral erythemal response multiplied by the spectral-energy distribution of the source and is analogous in principle to the luminosity curve of the eye for a source of visible light. The erythematic effect is indicated in Fig. 1-15.

During all work with ultraviolet rays it is necessary to protect the eyes with suitable glasses, since it has been found that exposure of the unprotected eye to light of short wave lengths extending far into the ultraviolet produces very serious and often lasting injuries to this organ.

Ultraviolet radiation is used for various unrelated purposes in many industries. In some cases it is used to replace sunlight when the ultraviolet properties of sunlight are desired. Among these applications are the testing of dyes, paints, etc., as to permanency of color and of substances which deteriorate in sunshine such as paper, rubber, glass, foods, flavoring extracts, etc.

Numerous other applications are the ultraviolet irradiation of foods and sources of food, *e.g.*, plants and animals, to produce the vitamin *D*. Another application is the killing of bacteria as an aid to the preservation of food and purification processes.

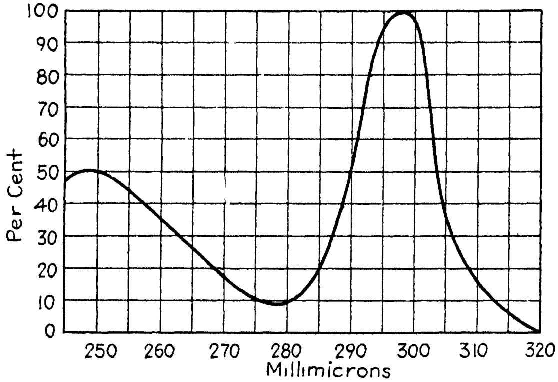

FIG. 1-15.—Erythematic effect. (*Hausser & Vahle.*)

This short-wave radiation is used in many manufacturing processes, in medical treatments, photographic applications, and spectacular lighting effects. There is reason to believe that the future will see a great increase in the application of this radiant energy to the needs of the industrial world.

Ultraviolet Luminescent Effects.—It has been found that certain substances are capable of transforming the longer wave lengths of the ultraviolet (3200 to 4200Å.) radiation into longer waves of the visible spectrum. Pigments extracted from these substances are used in "ultraviolet paints" and become luminescent when exposed to ultraviolet radiation.

Two kinds of paints known as fluorescent and phosphorescent have been developed. Fluorescent pigments are those made luminous by ultraviolet radiation and are available in nearly all colors of the rainbow. Phosphorescent paints emit a self-luminous glow for some time after the ultraviolet source is removed and are available in several colors.

The characteristics of these two types of paints make possible two distinctly different luminous affects when used jointly in a single composite design. The increase in the application of ultraviolet effects has led to the development of the dense blue glass mercury-vapor tube and finally, the "black-bulb" mercury-vapor lamp. This latter lamp is similar to the ultraviolet health lamp in construction details and operating characteristics, but is provided with a special, dense purple glass bulb which absorbs nearly all the visible light yet transmits a high percentage of the ultraviolet.

An illustration of effects produced is a wallpaper that exhibits a simple conventional design of cross-section lines when viewed in ordinary light. Under ultraviolet radiation this simple design is transformed into a beautiful luminously colored sea garden containing flowering plants and various fish. The ceiling is changed to a sky at night, studded with luminous stars.[1]

Many theatrical productions have enhanced the beauty of their settings and effected dual scenes on the same curtain drop through the use of luminous paints. For this purpose quartz-tube mercury lamps with special glass filters concealed as footlights in troughs on the stage may be used as the source of ultraviolet light.

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CHAPTER II

PHOTOMETRIC STANDARDS, UNITS AND NOMENCLATURE

PHOTOMETRIC STANDARDS

Standards of luminous intensity or candle power are devices for producing visible radiation of constant and measurable value. Those existing or proposed secure this constancy of luminous radiation by three methods:

1. By the first method the flame standards are used. In the construction and use of this class certain specifications are closely followed, and their accuracy is based on the assumption that if these specifications are followed the standard intensity will be reproduced. These specifications refer to such details as the size, material and weave of the wick, the size and construction of the burner and chimney, the composition and rate of combustion of the fuel, and the pressure and humidity of the atmosphere.

2. By the second method the intensity of radiation is controlled by the observation or measurement of some accompanying physical variable, *e.g.*, temperature. The Violle platinum standard, the arc standard, and the black-body standard belong to this class.

3. By the third method it is proposed that the intensity of visible radiation be controlled by the direct measurement of the radiation, as radiation. To this class belong the three-spectral line standard proposed by Steinmetz and the "definite quantity of the most efficient possible radiation" standard proposed by Ives.

The standard of luminous intensity was, for a time, the light of a candle made to certain specifications and consumed at a given rate; and it has been the almost universal custom to refer the intensity of a light source to that of the candle and to give the value of its luminous intensity in terms of the candle or candle power.

The flame standards of luminous intensity which have been used to quite an extent in the past are the English and German candles, the Carcel lamp, the Methven screen, the kerosene standard, the pentane standard, and the Hefner lamp.

Since seasoned incandescent lamps properly certified have replaced the flame standards for photometric work, and since a description of the various flame standards may be found in any of the books on photometry, of an earlier date, only the Hefner lamp will be described here.

The Hefner Lamp.—The most successful primary flame standard is the Hefner amyl acetate lamp. This lamp is especially favored in Germany and is the official standard recognized by the Physikalisch-Technische Reichsanstalt. It has been subjected to thorough and accurate investigations and its faults as well as its merits are clearly understood.

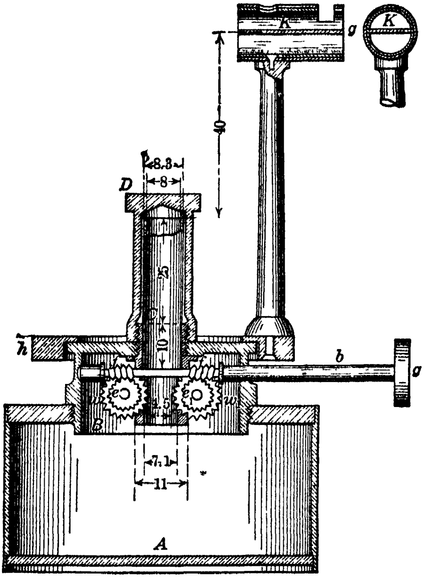

FIG 2-1 —The Hefner lamp.

The Reichsanstalt lamp has been universally adopted as the standard for the use of amyl acetate. The lamp is constructed of brass, except for the wick tube, which is of German silver to prevent corrosion by the combustible. The wick is moved by a worm gear, which actuates two spur wheels, shown in Fig. 2-1. All the fittings of the lamp are attached to the wick tube, which unscrews from the cup for filling. The character of the wick has practically no influence on the candle power of the lamp, since amyl acetate vaporizes at such a low temperature that the wick does not project into the flame and burn. A metal cap is kept screwed down over this wick when the lamp is not in use.

A test gauge is furnished with each lamp for adjusting the height of the flame, which burns with greatest constancy and steadiness when about 40 mm. in height. Accuracy in setting the flame is essential, since a variation of 1 mm. in height will produce about 3 per cent difference in the illuminating power. Under the above conditions and with normal atmospheric pressure and humidity the horizontal intensity of the flame is 0.9 candle power.

It was also found that an increase or decrease of 1 mm. in the diameter of the wick tube caused a variation of 1 per cent in the light intensity.

Von Hefner-Alteneck, the inventor of this lamp, pointed out and insisted on the necessity of using a combustible of known chemical composition. Amyl acetate ($C_7H_{14}O_2$), because of its chemical simplicity and definite composition, is excellent as the combustible of a standard. It is a colorless liquid and burns with a clear, not very brilliant, somewhat reddish flame. It is obtained from the distillation of amyl alcohol, obtained from fusel oil, with a mixture of acetic and sulphuric acids, or by distilling a mixture of ethyl alcohol, sulphuric acid, and potassium acetate. Impurities, which are most common in amyl acetate, have little effect upon the value of the light from this lamp.

Amyl acetate should be kept in a glass-stoppered bottle and, as it has a tendency to decompose in strong light, it should be stored in a dark place or in opaque vessels.

The temperatures produced by the lamp itself are rendered negligible by the thinness of the walls of the tube, while atmospheric temperatures have no discernible influences.

Atmospheric moisture, however, is not without its effect. Data showing the monthly averages for the light of the Hefner lamp for one year vary from 101.9 per cent normal candle power for February to 97 per cent for July. During March, April, May, October, and November the average intensity was normal. For June, July, August, and September the average was about 2 per cent below normal, and for December, January, and February the average was about 2 per cent high. The results of tests extending through two years showed a maximum difference of

8.5 per cent, or 103.3 per cent in January and February, and 94.8 per cent in May and July. Hence this lamp can be relied upon to give values within 4 per cent of the normal standard candle power.

The relation between the candle power of the Hefner lamp, the humidity and the barometric pressure is given in the following equation:

$$I = 1 + 0.0055(8.8 - v) - 0.00011(760 - p) \qquad (2\text{-}1)$$

where I = candle power,
v = water vapor per cubic meter of air, liters,
p = atmospheric pressure of mercury, millimeters.

The room should be well ventilated to eliminate errors due to change in carbon dioxide content.

Tests as to the accuracy and constancy of the Hefner lamp have given satisfactory results. The chief objection to this lamp as a standard is that the flame is too red, thus making it difficult to eliminate errors in photometry.

The Arc Standard.—The arc standard is the name applied to a standard in which it is proposed to use the light from the positive crater of a carbon arc. It has been found that the intrinsic brightness of the positive crater between pure carbon electrodes possesses remarkable constancy with varying specific consumptions of energy.[1] The question of reproducibility appears to be dependent only on the location of the crater and the use of a standard quality of carbon electrode.

The Black-body Standard.—It has been proposed to define the unit of light as the physiological effect of the equivalent of 1 watt of visible radiation. Since this assumption requires a definition of the distribution of energy throughout the visible region, it was further suggested to accept the visible radiation from a black body at such a temperature that the ratio of the radiation in two definite regions of the spectrum have a specified relation as such a definition.

It is obvious that such a source possesses unfavorable characteristics, *e.g.*, the deviation of the radiator from a black body; unequal absorption of the glass envelope to energy of different wave lengths; liability of inaccuracy in locating the proper limit in the red portion, which would seriously affect the results because of the magnitude of the radiation in this region compared with the physiological effect; and the color of the light, which must be yellow instead of white because of the temperature limitations imposed by the radiator.

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[1] *Proc. Roy. Soc.* (*London*), vol, 27, p. 157, 1879.
Bur. Standards, Bull., vol. 1, p. 109, 1905.

Violle's Platinum Standard.—Violle's standard consists of the luminous radiation from 1 sq. cm. of incandescent platinum at the temperature of liquefaction. In some of the earlier investigations of this standard a lower temperature was used, but under these conditions it proved unsatisfactory. The rapid disintegration of the platinum gave considerable change in temperature for a given value of current. This unit, however, has much to recommend it. The temperature of the melting point of a pure metal can be accurately defined and reproduced. The composition of the light from melting platinum corresponds more nearly to that from modern light sources than does the light from the other standards previously mentioned. The larger value (20 bougies or candles) is another advantage. Experiments by Petanel,[1] in which he used hydrogen instead of coal gas in the blast lamp for melting the platinum, indicate that Violle's standard is neither impractical nor inaccurate.

The *bougie candle* is equal to 0.05 of the Violle, or to the light from 5 sq. mm. of incandescent platinum at the temperature of liquefaction.

The Waidner and Burgess Standard.—Several years ago Waidner and Burgess[2] suggested that the brightness of a black body at the temperature of freezing platinum be adopted as the standard of luminous intensity.

A few years ago Wensel and his coworkers[3] investigated the brightness of a black body at the temperature of freezing platinum as a possible standard of luminous intensity. They made and used several special black bodies that could be immersed in the molten platinum. In these tests four different ingots of very pure platinum were used and several hundred determinations were made of the temperature of the freezing platinum and of the brightness of the black body at this temperature.

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[1] *Proc. Roy. Soc. (London)*, vol. 65, p. 469, 1900.

[2] *Elec. World*, vol. 52, p. 625, 1908.

[3] *Bur. Standards J. Research*, vol. 6, p. 1103, 1931.

Work has been done on this standard of intensity in England, Germany, and France. Although not completed in the laboratories of Germany and France (1935), the temperatures brightness values reported are given in Tables 2-1 and 2-2.[1]

TABLE 2-1.—SUMMARY OF TEMPERATURE MEASUREMENTS OF FREEZING PLATINUM

National Bureau of Standards (United States)	1773.5°C. ± 1°
Physikalisch-Technische Reichsanstalt (Germany)	1773.8°C. ± 1°
National Physical Laboratory (England)	1773.3°C. ± 1°
Mean	1773.5°C.

The greatest departure from mean 0.3°C. would correspond to 0.1 per cent in candle power.

TABLE 2-2.—SUMMARY OF BRIGHTNESS MEASUREMENTS OF BLACK BODY AT FREEZING POINT OF PLATINUM

	Candle Power Square Centimeter
National Bureau of Standards (United States)	58 84
Riband (France)	58.78
National Physical Laboratory (England)	58 9
Mean	58.85

From these results it would seem that the national laboratories were about to produce a primary standard of luminous intensity worthy of the name.

Object of a Primary Standard.—The object of the primary standard is, obviously, not to obtain a working standard for laboratory purposes but rather a reproducible unit to which reference may be made from time to time to prevent any drifting in one way or another which is likely to occur in the status of the arbitrary standard of luminous intensity in vogue at the present time. None of the primary standards already in use is by any means satisfactory, either from the scientific or from the practical side. They are in no way connected with the fundamental units of space, mass, and time. Until thus coordinated, they may be considered as little more than convenient arbitrary references to be used in practice, pending the determinations of their real values.

The sensation of light is caused by the impinging of radiant energy upon the retina; consequently, it seems only logical that the scientific specifications for the standard of light should be based on the measurement of radiation.

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[1] FORSYTHE, *Trans. Illum. Eng. Soc.*, vol. 31, p. 181, 1936.

The complexities and difficulties arising in connection with the development of such a standard are obvious. It was shown in the preceding chapter that mere intensity of radiation is not an indication of luminous intensity, for not only is a large part of the radiation from most artificial light sources invisible, but even the visible part varies greatly in effectiveness in producing the sensation of brightness. Moreover, the mode of action of the eye is such that the luminous equivalent of radiation of a certain spectral wave length varies with the absolute intensity.

Proposed Radiation Standard.—A primary standard based on the measurement of radiation was proposed by Steinmetz[1] in 1908. He suggested the selection and mixture of three primary colors of the visible spectrum, *viz.*, blue, green, and red, in definite proportions, so chosen as to give a white or yellowish-white light. A comprehensive treatment of possible standards of this type is given in a paper by Ives,[2] to which the reader is referred for greater details. In this paper it is stated, in reference to a possible three-line standard, that, from the standpoint of purity in respect to the primary sensations, the colors possessing the nearest claims to primary colors are a red of greater wave length than 0.64μ, a green of 0.506μ, and a blue of 0.48μ. These wave lengths are almost exactly furnished by an arc between cadmium electrodes. Moreover, it is these three cadmium lines, red (0.6439μ), green (0.5086μ), and blue (0.4800μ), that are the standards of wave length in terms of which the standard meter bar at Paris has been calibrated by Michelson. It is suggested that, if a three-line standard ever should be considered seriously, it would be well to consider the advisability of having the same source which furnishes our ultimate standard of length also furnish our ultimate standard of luminous intensity.

While the three-line standard permits the making of a standard of any desired color, the specification of the radiation-light relationship is complicated, and spectroscopic, radiometric, and photometric difficulties render it probably impractical.

Ives suggests as a standard a *definite quantity of the most efficient possible radiation.* This could be achieved practically by measuring as both radiation and light a monochromatic radiation whose luminous efficiency is known. The green radiation of mercury actually corresponds, within the limits of present measurements, to the most efficient possible radiation and suggests itself as a practical means of obtaining this standard. It may be obtained from the quartz-mercury arc in sufficient quantity for both radiometric and photometric purposes and may be easily isolated by color screens. No spectroscopic device is necessary for separating this line from the others. A sheet of neodymium glass will obstruct the neighboring yellow lines. A solution of potassium bichromate in a glass trough will obstruct the blue, violet, and ultraviolet radiation.

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[1] Steinmetz, *Trans. Am. Inst. Elec. Eng.*, vol. 27, p. 1319, 1908.

[2] Ives, *Trans. Illum. Eng. Soc.*, vol. 6, p. 258, 1911.

Thus an absorption cell can be easily prepared through which green radiation will pass in great intensity and purity.

Such a standard has much in its favor. Compared with a three- or two-line standard its theoretical simplicity is evident. It possesses the simplest possible relationship between radiation and light. Its establishment as a primary standard would make the unit of light the watt per square centimeter of the most efficient possible radiation. The lumens emitted by any given source would be obtained at once by multiplying its consumption in watts by the "reduced luminous efficiency" of the source.

Later Houstoun[1] and Strache[2] suggested the specification of a standard in terms of radiation weighted as light. Houstoun would do this by a special absorbing screen, Strache by a template over the spectrum. Parts of the spectrum are then recombined. Both of these suggestions, when analyzed, consist in specifying the light standard by the least quantity of radiated energy that can produce the standard intensity.

The Incandescent Lamp as a Comparison Standard.—The incandescent lamp, aside from its illuminating value, is of inestimable value as a secondary or comparison standard of light. The incandescent lamp has probably been of more service in photometry than any other source of light, because of the constancy of the luminous intensity of a particular filament under proper conditions. This attribute has made possible concordant data and a quantitative knowledge of the variations in flame standards. The color of the light from an incandescent lamp, especially if the lamp has a metallic filament, can be varied by changing the voltage so as to resemble the compared light in many cases. They may be moved along the photometer bar at the pleasure of the operator and are portable, making them convenient in portable photometers where a low-voltage lamp may be used in conjunction with a storage battery or dry cells.

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[1] HOUSTOUN, *Proc. Roy. Soc. (London)*, vol. 85, p. 275, 1911.

[2] STRACHE, *Zeit. Beleuchtungsw.*, 1911.

It can be seen from the life curves of incandescent lamps that a lamp is not suitable for a standard until it has been in operation for 50 or 100 hr. After burning about this length of time its performance becomes less variable, and it is at this period of its existence that it should be standardized.

When possible, the illuminating power of a lamp to be used as a standard should be determined by comparison with the standards maintained at the Bureau of Standards or some laboratory qualified to do this work. It is well to keep one or more carefully standardized lamps for occasionally checking the working standards. The temporary set or hysteresis in the resistance of the filament, and especially the permanent set due to abnormally high voltages, should be avoided. A lamp should not have voltages impressed upon it much in excess of that at which it is aged and calibrated.

It is necessary to know the position of the lamp relative to the photometric axis when being standardized, and the voltage, current, or wattage at which it was standardized, in order to be able to reproduce known conditions. Incandescent lamps are usually operated as standards at a constant voltage, the current being used as a check. Sometimes they are operated at constant current and the voltage varied slightly if necessary. The method would be immaterial, provided there was no change in the resistance of the filament during its period of operation. The best performance of a standard will be obtained by operating it at such voltage or current as to maintain the wattage constant.

In photometry it often becomes desirable, where exact voltage regulation is impossible, to correct the values of intensity obtained for variations in voltage. In order to do this, a knowledge of the performance of the unit under those conditions is desirable. It has been found that for incandescent lamps the candle power can be represented over a small range by the equation

$$I = aV^k \tag{2-2}$$

where I = candle power
V = voltage
a and k = constants.

If I_0 be the candle power at a voltage V_0, then the candle power I_x at some other voltage E_x may be found by the expression

$$I_x = \left(\frac{V_x}{V_0}\right)^k I_0 \tag{2-3}$$

The value of k for a tungsten-filament lamp is 3.51, for the vacuum lamp and 3.38 for the gas-filled lamp. For the carbon lamp of 3.1 watts per mean horizontal candle power the value of k is 5.4.

The Gas-filled Lamp as Photometric Standard.[1]—The Bureau of Standards has used gas-filled lamps as photometric standards since 1917. A careful study of data extending over a period of 12 years showed lamps of the 500-watt size have kept their relative positions in a group within 0.03 per cent for a period of about 35 hr. of burning. It was found that the mean of a group of 500-watt gas-filled lamps, of the type used by the Bureau as working standards, decreased 0.018 per cent for each 5 hr. of burning.

Lamps of the 200- and 100-watt sizes gave evidence of a constancy, with reference to the mean of the group, comparable with the 500-watt lamps.

The unit of candle power as agreed upon by the leading nations in 1909 was maintained through the medium of carefully made carbon-filament lamps. In transferring to the gas-filled lamp as the medium for maintaining the value of the candle there is a possible chance of a shift in the value of the candle. International checks on the value of the unit appear to indicate this.

It was found that the value of the candle differed in magnitude in different countries when applied to lamps of different efficiencies. Progress has, however, been made internationally by laying down an agreed method for transferring from one color-temperature lamp to another, *i.e.*, carbon (about 2000°K.) to vacuum tungsten (about 2350°K.), and vacuum tungsten to gas-filled tungsten (about 2800°K.).[2] The results of applying this method are now being evaluated in terms of the actual percentages by which the lamp industry of each country will have to raise or lower its various lamp ratings in order to come into general agreement.

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[1] R. P. Teele, *Trans. Illum. Eng. Soc.*, vol. 25, p. 78, 1930.

[2] *Inst. Elect. Eng.* (*London*), vol. 78, p. 171, 1936.

For deriving tungsten standard lamps from the carbon-filament standards through the medium of which the value of the international candle was first established and maintained the International Commission on Illumination adopted the filter method. A blue glass filter was adopted of such spectral transmission that when used with the carbon lamp the color would match that of a 1.25 watts per mean horizontal candle power vacuum-tungsten standard. The same filter when used with the vacuum-tungsten lamp gave a very approximate color match for determining the mean spherical candle power of a 500-watt standard.

Definitions and Nomenclature.—The units of illumination and photometry and the terminology used in this text are based on those approved by the American Standard Association.[1]

The luminous intensity of a source of light I is expressed in candle power or candles.

Candle power refers to the luminous intensity of a source of light. It refers to the intensity only in some direction such as the horizontal, vertical, or at some angle with the vertical. It gives no measure of the total light emitted or the illuminating value of the source. The candle power of a source in a given direction is equal to the normal incident illumination (E_n) in foot-candles on a surface normal to that direction multiplied by the square of the distance in feet.

$$I = E_n r^2 \tag{2-4}$$

The *candle* is the unit of luminous intensity and is maintained at the Bureau of Standards through the medium of incandescent lamps. It was established by agreement between the national standardizing laboratories of France, Great Britain, and the United States, and adopted in 1921 by the International Commission on Illumination.

The *mean horizontal candle power* (I_h) of a lamp is the average candle power in the horizontal plane passing through the luminous center of the lamp (Fig. 2-2*B*).

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[1] *Trans. Illum. Eng. Soc.*, vol. 28, p. 265, 1933. *A.S.A.* No. 27, 1932.

The *mean spherical candle power* (I_{ms}) is the mean of the intensities radiating in all directions from the source as a center. It is equal to the light flux in lumens divided by 4π

$$I_{ms} = \frac{F_s}{4\pi} \tag{2-5}$$

Since there are 4π solid angles emanating from a point the mean spherical candle power is the average flux in lumens per unit solid angle.

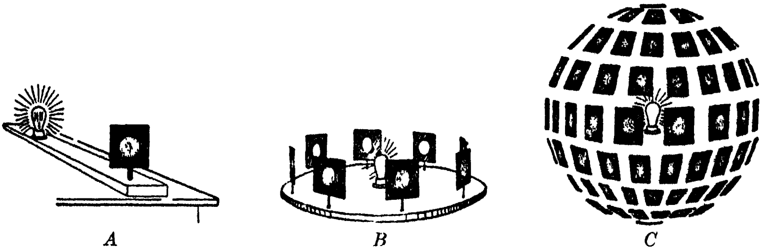


FIG. 2-2.—Measurement of candle power *A*, horizontal, *B*, mean horizontal, *C*, mean spherical

The *mean lower hemispherical candle power* (I_{lh}) and the *mean upper hemispherical candle power* (I_{uh}) refer to the mean of the intensities in all directions below and above a horizontal plane through the source. These values are also equal to the flux in the respective hemispheres divided by 2π.

$$I_{lh} = \frac{F_{lh}}{2\pi} \quad \text{and} \quad I_{uh} = \frac{F_{uh}}{2\pi} \tag{2-6}$$

The (mean) *zonal candle power* of a lamp is the average candle power of the lamp over the given zone. It is equal to the luminous flux in that zone divided by the solid angle of the zone.

$$I_z = \frac{F_z}{\omega_z} \tag{2-7}$$

The *apparent candle power* of an extended source of light measured at a specified distance is the candle power of a point source of light which would produce the same illumination at that distance.

The *spherical reduction factor* is the ratio of the mean spherical candle power to the mean horizontal intensity. Hence the mean spherical candle power is equal to the product of the mean horizontal candle power and the spherical reduction factor. The total flux of light in lumens is equal to 4π multiplied by the product of the mean horizontal candle power and the spherical reduction factor.

$$I_{ms} = fI_h \qquad \text{and} \qquad F = 4\pi fI_h \tag{2-8}$$

The *intensity of illumination* is measured in foot-candles or lumens per square foot.

The *foot-candle* is the normal incident illumination produced by unit candle power at a distance of 1 ft. When the average illumination on a square foot of surface is 1 foot-candle the light flux thereupon will be 1 lumen and the intensity 1 lumen per square foot. Hence it follows that the average illumination of a surface in foot-candles is equal to the flux of light in lumens falling on the surface divided by the area of the surface in square feet.

$$E = \frac{I}{r^2} = \frac{F}{S} \tag{2-9}$$

The intensity I in candle power is the angular density of the flux and the illumination intensity E is surface density. Therefore both I and E are flux ratios, lumens per unit solid angle and lumens per unit area. One lumen per unit solid angle is the candle and 1 lumen per square foot is the foot-candle.

The *meter-candle* or *lux* is the normal incident illumination intensity produced by 1 candle power at a distance of 1 m. One lumen per square meter is the meter-candle or lux.

The *phot* is equal to 1 lumen per square centimeter.

The *lumen* is the unit of luminous flux radiated and is equal to the amount of luminous flux received on an area of 1 sq. ft. on the surface of a sphere having a radius of 1 ft., from a uniform point source having an intensity of 1 candle power, placed at its center (Fig. 2-3). This is equivalent to stating that it is the luminous flux emitted in a unit solid angle from a uniform point source of 1 candle power. From this it follows that a uniform point source of 1 candle power produces a total luminous flux of 4π lumens.

Illumination is the density of luminous flux per unit area. It is independent of the character or color of the surface upon which it is received, and must not be confused with the brightness of the surface. For example, a black surface and a white surface may receive the same illumination but the black surface which absorbs the luminous flux will not appear so bright as the white surface which reflects it.

The *luminosity curve* is a curve showing luminous flux per element of wave length as a function of wave length. Therefore it gives, wave length by wave length, the product of the radiant flux and the visibility.

The *luminous efficiency* of radiant energy is the ratio of the luminous flux to the radiant flux. Luminous efficiency is usually expressed in lumens per watt of radiant flux.

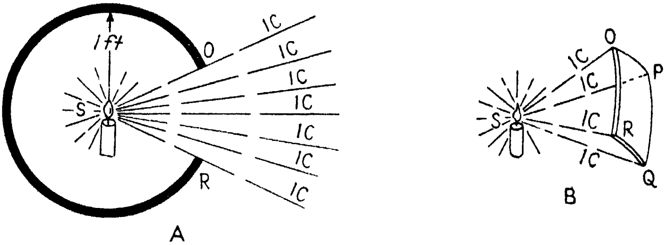


FIG. 2-3.—*A*, opening *OR* has area of 1 square foot and emits 1 lumen. *B*, 1 lumen falls on surface *OPQR*

The *efficiency* of a source is the ratio of the total luminous flux to the total power consumed. In an electric lamp it is expressed in lumens per watt.

The *coefficient of utilization* of an illumination installation on a given plane is the total flux received by that plane divided by the total flux from the lamps illuminating it. When not otherwise specified, the plane of reference is assumed to be a horizontal plane 30 in. (76 cm.) from the floor.

The *brightness* of a surface, whether it is a luminous source or a reflecting surface, depends upon the character and color in addition to the value of the illumination emitted or received by it. Brightness may be expressed in two ways: (*a*) by its luminous intensity in candles per square centimeter and (*b*) by the luminous flux emitted by unit area of the surface, the unit being the lambert.

The *lambert* is the unit of brightness and is equal to the uniform brightness of a perfectly diffusing surface emitting or reflecting light at the rate of 1 lumen per square centimeter. It is also the *average* brightness of *any* surface emitting or reflecting light at the rate of 1 lumen per square centimeter.

Brightness expressed in candles per square centimeter may be reduced to lamberts by multiplying by π (3.1416).

The *foot-lambert* is a unit of brightness equal to the average brightness of any surface emitting or reflecting light at the rate of 1 lumen per square foot.

The average brightness of any reflecting surface in foot-lamberts is therefore the product of the illumination in foot-candles by the reflection factor of the surface. The foot-lambert is the same as the "apparent foot-candle."

A *primary luminous standard* is one by which the unit of light is established and from which the values of other standards are derived. A satisfactory primary standard must be reproducible from specifications.

A *secondary standard* is one calibrated by comparison with a primary standard. The use of the term may also be extended to include standards which have not been directly measured against the primary standards, but derive their assigned values indirectly from the primary standards.

Because of the lack of a satisfactory primary standard of light the unit is actually maintained in most laboratories by electric incandescent lamps serving as reference standards. The values assigned to these standards were originally agreed upon as representing the average value of the accepted primary standard as nearly as this could be determined.

A *working standard* is any standardized luminous source for daily use in photometry.

A *comparison lamp* is a lamp of constant but not necessarily known candle power against which a working standard and test lamps are successively compared in a photometer.

A *test lamp*, in a photometer, is a lamp to be tested.

A *performance curve* is a curve representing the behavior of a lamp in any particular (candle power, consumption, etc.) at different periods during its life.

A *characteristic curve* is a curve expressing a relation between two variable properties of a luminous source, *e.g.*, candle power and voltage, candle power and rate of fuel consumption, etc.

A *curve of light distribution* is a curve showing the variation of luminous intensity of a lamp or luminaire with angle of emission.

A *curve of horizontal distribution* is a curve, usually polar, representing the luminous intensity of a lamp or luminaire at various angles of azimuth in the horizontal plane through its light center.

It is recommended that in horizontal distribution curves there be indicated the relative positions of parts of the equipment affecting the symmetry of distribution.

A *curve of vertical distribution* is a curve, usually polar, representing the luminous intensity of a lamp or luminaire at various angles of elevation in a vertical plane passing through its light center.

A *luminaire* is a complete lighting unit consisting of a light source, together with its direct appurtenances, such as globe, reflector, refractor, housing, and such support as is integral with the housing. The term is used to designate completely equipped lighting fixtures, wall brackets, portable lamps, so-called removable units, or street lighting units. In the last, the pole, post, or bracket is not considered a part of the luminaire.

Regular or specular reflection is that in which the angle of reflection is equal to the angle of incidence.

Diffuse reflection is that in which the light is reflected in all directions.

Perfectly diffuse reflection is that in which the reflected light is distributed in accordance with the cosine law, so that the reflecting surface appears equally bright from all angles of view. The reflection from a body may be regular, diffuse, or mixed. In most practical cases there is a superposition of regular and diffuse reflection.

Diffuse transmission is that in which the transmitted light is emitted in all directions from the transmitting body

Regular transmission is that in which the transmitted light is not diffused. In such transmission the direction of a transmitted pencil of light has a definite geometrical relation to the corresponding incident pencil. When the direction of the light is not changed the transmission is called direct.

Perfectly diffuse transmission is that in which the transmitted light is distributed in accordance with the cosine law, so that the surface of the transmitting body appears equally bright from all angles of view. The transmission of light by a body may be regular, diffuse, or mixed. In many practical cases there is a superposition of regular and diffuse transmission.

TABLE 2-3.—EQUIVALENTS AND CONVERSION FACTORS

Illumination

1 foot-candle = 1 lumen incident per square foot
= 10.76 lux
= 1.076 milliphots
1 lux = 1 lumen incident per square meter
= 0.0929 foot-candle
= 0.0001 phot
= 0.1 milliphot
1 phot = 1 lumen incident per square centimeter
= 10,000 lux
= 929 foot-candles
1 milliphot = 0.001 phot
= 0.929 foot-candle
= 10 meter-candles

Brightness

1 lambert = 1 lumen per square centimeter
= 0.3183 candle per square centimeter
= 2.054 candles per square inch
= 929 foot-lamberts
1 foot-lambert = 1 lumen per square foot
= 1.076 millilamberts
= 0.00221 candle per square inch
= 0.000343 candle per square centimeter
= 0.001076 lambert
1 millilambert = 0.001 lambert
= 0.929 foot-lambert
1 candle per square centimeter = 3.1416 lamberts
= 2919 foot-lamberts
1 candle per square inch = 0.487 lambert
= 487 millilamberts
= 452 foot-lamberts
1 candle per square foot = 3.1416 foot-lamberts
= 3.831 millilamberts

Reflection, Absorption, and Transmission.—Rays of light falling upon a surface are *reflected*, *absorbed*, or *transmitted* and perhaps refracted according to the nature of the substance of which the surface is composed.

Reflection.—The amount of light *reflected* from a particular surface depends upon (*a*) the molecular condition or color of the surface, (*b*) the angle of incidence or the angle which the rays make with a normal to the surface, and (*c*) the wave length or color of the incident rays. If the surface is smooth, the reflection is *specular* and the rays make an angle with a normal to the surface equal to the angle of incidence. If the surface is rough the reflected rays are *diffused.* By a proper choice and arrangement of the molecules of a substance rays of a desired frequency may be reflected and all others absorbed, thus giving rise to the color of the body. Substances differ greatly in their properties of absorption and reflection, and to these differences are due the variety of colors of objects.

Transmission and Absorption.—It is obvious that the amount of light transmitted by a translucent medium depends upon the quality of the medium and the color of the light transmitted and is equal to the difference between the amount of light received and the amount reflected and absorbed.

The amount of light absorbed by the globes and glassware used with lamps to prolong the life of the filament or of the electrode, to diffuse the light and lower the intrinsic brightness of the source, or to transmit light of a desired color may vary from 5 to 95 per cent owing to the difference in the thickness, density, or color, of the glass.

It is obvious that the percentage of light absorbed by an opaque surface is equal to 100 minus the percentage reflected. The amount transmitted by a translucent material is equal to the total incident light less that reflected and that absorbed in transmission.

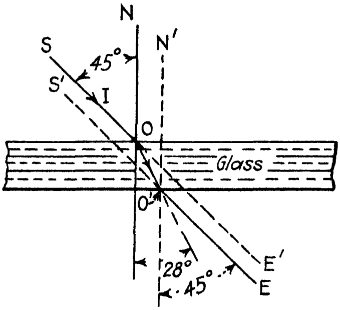


FIG. 2-4.—The principle of refraction.

Refraction.—Refraction is the change in the direction of light rays when they pass from one transparent medium to another of different density. This change is illustrated in Fig. 2-4, when light from a source S strikes the surface of a piece of glass having smooth, parallel sides. The rays are refracted upon entering the glass and again, in the reverse order, upon leaving the glass. If the two surfaces of the glass were not parallel, the direction of the transmitted rays would be modified accordingly.

If the eye be placed at E, the light would appear to come from S' instead of S. The manufacture of lenses is based on this principle of refraction.

The ratio of the sine of the angle of incidence to the sine of the angle of refraction is termed the *index of refraction,* which, in Fig. 2-4, is

$$\frac{\sin 45°}{\sin 28°} = \frac{0.707}{0.470} = 1.51 \tag{2-10}$$

The diffraction of prisms is used in the study of the spectrum of lights (Fig. 2-5) and in redirecting light from directions where it is not needed to regions where it will be useful.

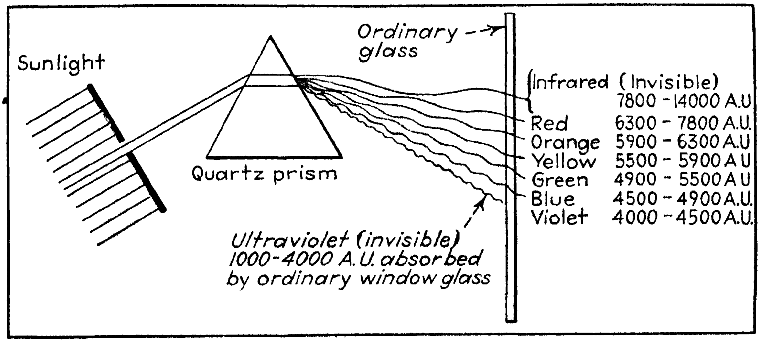


FIG. 2-5.—Sunlight passing through a quartz prism is broken into its well-known components—the visible colors of the rainbow, and the invisible parts, infrared and ultraviolet.

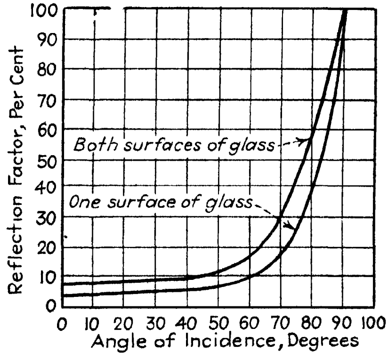


FIG. 2-6.—Reflection of light from clear plate glass; angles measured from a perpendicular to the surface.

Reflecting Surfaces.—As an illustration of the foregoing characteristics of materials assume that light rays fall on a piece of plate glass along a vertical angle. About 4 per cent will be reflected from its upper surface and 3 or 4 per cent from its lower surface; about 85 per cent will be transmitted and some 5 to 8 per cent will be absorbed. When light strikes glass at an angle from normal the amount of light reflected from the upper surface increases to a marked degree so that at 85 deg., for instance, nearly all of the light is reflected; very little is transmitted and that transmitted is refracted. Figure 2-6 shows the percentages of reflected light for different angles of incidence.

The reflection and diffusion characteristics of some of the materials used in globes and reflectors are shown in the following illustrations. These illustrate the principles of the different types of reflections and transmissions met in practice.

Polished metal reflectors give specular reflection as shown in Fig. 2-7. They are used extensively where they can be tightly enclosed to keep out the dirt and dust, *e.g.*, headlights, spotlights, etc. The characteristics of chromium-plated reflectors are desirable for commercial use. They may be finished dull or bright and have a high, reasonably constant reflection factor of about 65 per cent.

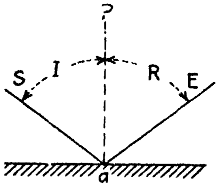


FIG. 2-7.—Reflection from polished surface.

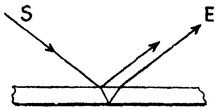


FIG. 2-8.—Reflection from mirrored surface

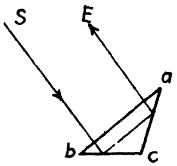


FIG. 2-9.—Reflection by prism.

A silvered glass mirror is illustrated in Fig. 2-8. A small part of the light is reflected by the polished surface of the glass; the remainder passing through the glass to the silver, from which it is reflected back through the glass again. Since the greater part of the light reflected has to pass through the glass twice by which some is absorbed each time the reflection factor of a mirror may be around 75 per cent, whereas the polished silver alone may show around 90 per cent. The glass preserves the polished condition of the silver but makes the unit susceptible to breakage.

Striations produced on surfaces illuminated by mirrored reflectors may be eliminated by fluting the reflector or frosting the lamp, with some loss of control of the light.

Prismatic refractors and reflectors involving the refracting and reflecting principles of the prism (see Figs. 2-9 and 2-10) are used in illuminating engineering to direct light where it will be more useful. Refracting prisms are used to produce a desired distribution of light as in street lighting units and in lenses for signals and lighthouse service. Prismatic glass is used in luminaires for many lighting installations.

Dull-finish metal reflecting surfaces, *e.g.*, aluminum paint, give a spread or semiregular reflection (Fig. 2-11). Streaks and striations are largely eliminated, but such surfaces collect dirt quickly and are difficult to keep clean.

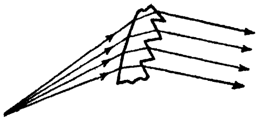


FIG. 2-10.—Refractions by prisms.

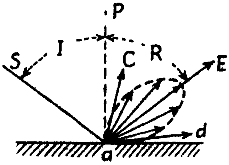


FIG. 2-11.—Reflection from semi-mat surface.

Rough or mat-finish surfaces reflect light in all directions. This is diffuse reflection, and is shown in Fig. 2-12. Surfaces such as plaster, calcimine, and wallpaper have the characteristics of mat-surface reflection.

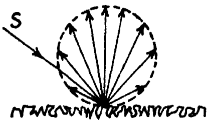


FIG. 2-12.—Reflection from rough mat surface.

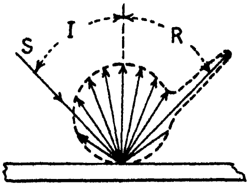


FIG. 2-13.—Reflection from porcelain-enameled steel.

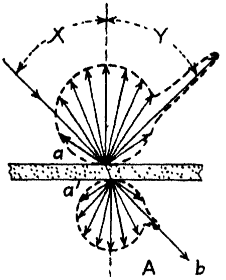
The porcelain-enameled metal reflector may be considered, so far as its optical characteristics are concerned, as a plate of white glass with a metal backing. The whiter and denser the enamel the higher will be the efficiency of the reflector. Its reflection is shown in Fig. 2-13. Its principal use is in industrial lighting.

White or milk glass is extensively used for reflectors, enclosing globes and for semienclosing units for schoolrooms, offices, general commercial lighting and in many types of industrial luminaires. It both reflects and transmits light, the proportions of each depending on the density of the glass. It has excellent diffusing properties, in both transmission and reflection of light (Fig. 2-14).

Frosted or etched glass gives a spread transmission of light as shown in Fig. 2-15. Its quality as a diffusing material is poor, and the rough surface accumulates dirt and is difficult to clean.

Stippled or pebbled glass has the diffusing properties of frosted glass without the difficulty of cleaning. Globes of this glassware are used in street lighting units.

The application and use of some of these materials and principles described on the preceding pages are illustrated in Fig. 2-16. These illustrations represent several types of reflecting, diffusing, and light-control units the applications of which will be discussed from time to time in the text.



2-14.—Reflection and transmission of milk glass.

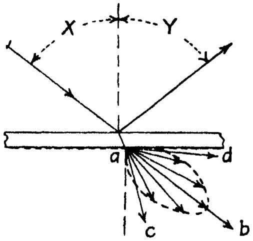


FIG. 2-15.—Reflection and transmission by etched glass.

umbert's Cosine Law of Incidence.—The illumination inten- upon a surface which is inclined to the direction of the light is less than it would be if the surface were perpendicular to rays and is equal to the illumination perpendicular to the tion of the light multiplied by the cosine of the angle of lence. Combining the inverse-square and cosine laws we get

$$\text{Illumination } E = \frac{I \cos a}{D^2} \qquad (2\text{-}11)$$

where I = candle power of the source
D = distance from the source
a = angle of incidence

The principle of this relationship is shown in Fig. 2-17.

Lambert's Cosine Law of Emission.—The intensity of light in a certain direction radiated or reflected by a perfectly diffusing

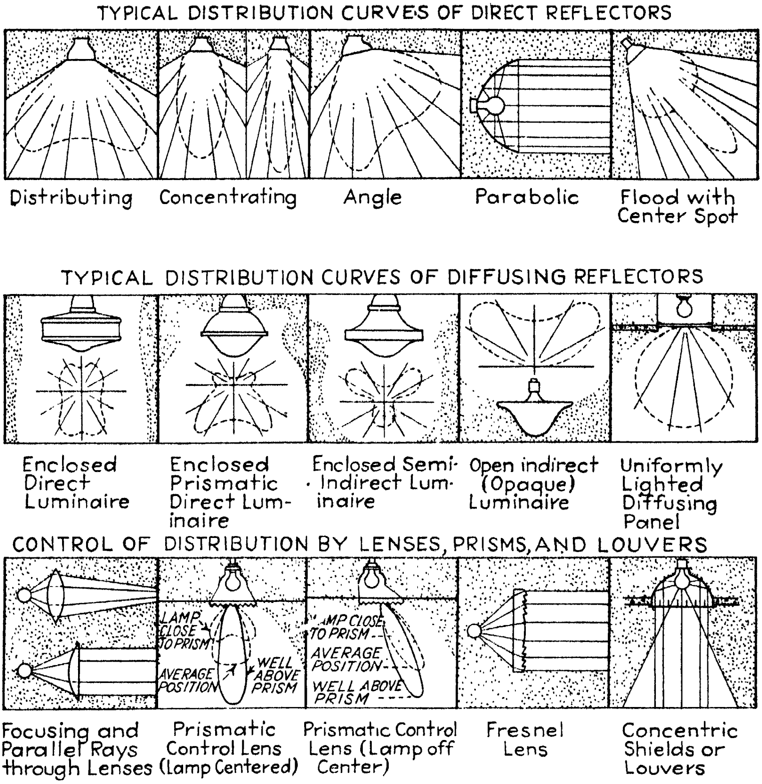

TYPICAL DISTRIBUTION CURVES OF DIRECT REFLECTORS
Distributing
Concentrating
Angle
Parabolic
Flood with Center Spot
TYPICAL DISTRIBUTION CURVES OF DIFFUSING REFLECTORS
Enclosed Direct Luminaire
Enclosed Prismatic Direct Luminaire
Enclosed Semi-Indirect Luminaire
Open indirect (Opaque) Luminaire
Uniformly Lighted Diffusing Panel
CONTROL OF DISTRIBUTION BY LENSES, PRISMS, AND LOUVERS
LAMP CLOSE TO PRISM
AVERAGE POSITION
WELL ABOVE PRISM
LAMP CLOSE TO PRISM
AVERAGE POSITION
WELL ABOVE PRISM
Focusing and Parallel Rays through Lenses
Prismatic Control Lens (Lamp Centered)
Prismatic Control Lens (Lamp off Center)
Fresnel Lens
Concentric Shields or Louvers

Fig. 2-16.—Methods of controlling the distribution of light by reflection, refraction, and diffusion.

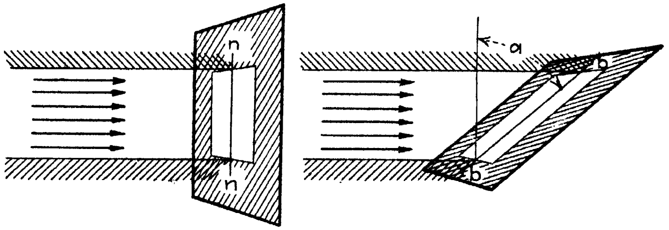


Fig. 2-17.—Lambert's cosine law of incidence. Illumination on *b* equals illumination on *n* times cos *a*.

plane surface varies as the cosine of the angle between the emitted ray and a normal to the surface. This is shown in Fig. 2-18 where the candle power normal to a surface S is I. Then in some other direction such as α deg. with the normal the candle power I_α will be

$$I_\alpha = I \cos \alpha \qquad (2\text{-}12)$$

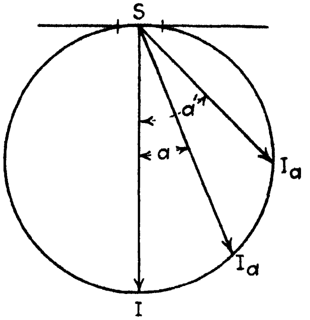


FIG. 2-18.—Lambert's cosine law of emission. I_α equals $I \cos \alpha$.

Glass.—The most important transmitting and diffusing medium for scientific and architectural lighting is glass. Most of the glasses of interest for this purpose diffuse or scatter the light and reduce the apparent brightness of the source. Ordinary window and bottle glass make up by far the greater part of the some three hundred million dollars' worth of glass manufactured annually in this country. The raw materials used in this glass are principally sand, lime (either raw or calcined) and soda ash, a form of soda such as may be obtained by heating ordinary washing soda to eliminate its water.

Lead glass contains lead oxide in place of lime and more or less potash in place of soda. It may contain 25 to 50 per cent or more of lead. Lead gives glass brilliance and makes a high polish possible in ornamental articles of cut glass. Lead glass is also more readily annealed and less likely to break after heating and for that reason, among others, was used until recently for making incandescent electric light bulbs.

The third important group of glasses with respect to chemical composition are the borosilicate glasses, which contain borax or boric acid or both. They are of value chiefly on account of their low expansion coefficient and resistance to dissolving action of chemicals. The Pyrex ovenware is of this group and is one of the harder glasses.

Commercial glasses will increase or decrease in length from three to eleven millionths per degree centigrade. For the Pyrex glasses the linear expansivity is around 3, and some of them can be sealed to porcelain, tungsten, and molybdenum, which have expansion coefficients of 4 or 5 on the same scale.

Quartz glass, which is not quartz but amorphous silica, has a linear expansivity of less than one millionth and can be heated to redness and plunged into cold water without breaking.

The heat conductivity of glass is about 0.3 per cent of that of copper and 1 to 2 per cent of that of iron.

Nomenclature and Characteristics.—The nomenclature and characteristics[1] for illuminating glasses[2] are as follows:

Solid opal glass is a homogeneous white glass, usually providing a high degree of diffusion.

Flashed or cased opal glass is a crystal glass with a thin coating of highly diffusing opal. Either the flashing or the clear glass may be in color.

Opalescent glass is a partially devitrified glass with crystalline material more or less uniformly scattered throughout. Tinges of color are usually visible and variegated effects are often present.

Alabaster glass is a semi-diffusing glass, usually of a gray, waxy appearance, with diffusing material held in colloidal suspension. For a given thickness, it usually has less diffusion than opal glass.

The true alabaster appearance results from the internal structure of glass of proper composition, rather than from surface treatment or casing. An alabaster appearance can also be obtained by casing an opal glass with clear glass, and, while this should be classed as a cased glass, it is sometimes referred to as alabaster.

Cased glass is composed of two or more layers of different glasses, usually a clear, transparent layer to which is added a layer of opal, opalescent, or colored glass. This glass is sometimes referred to as flashed, multi-layer, polycased, etc.

Configurated glass has a patterned or irregular surface. The surface configuration is usually applied during fabrication. It is not transparent and is somewhat diffusing.

Glasses falling under this classification are often referred to as pebbled, stippled, rippled, hammered, patterned, chipped, crackled, cathedral, etc., depending upon the particular type of surface.

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[1] *Trans. Illum. Eng. Soc.*, vol. 26, p. 1025, 1931; vol. 29, p. 677, 1935.

[2] Although the following definitions directly cover only colorless glasses, they may be extended to tinted or colored glasses by applying the proper adjectives in each case. For example, opal glass may possess an amber tint and may then be described as "amber opal glass."

Prismatic glass is a clear glass into the surface of which is fabricated a series of prisms, the function of which is to direct the incident light in desired directions.

Homogeneous glass has an essentially uniform composition throughout its structure. This term is used to distinguish it from cased glass which is composed of two or more layers of different compositions, rather than to appraise on the basis of freedom from streaks, striae, etc.

Enameled glass has had applied to its surface a coating of enamel. These enamels may be white or colored and may have varying degrees of diffusion.

Decorated glass is a glass to which etchings, stains, enamels, etc., are applied, primarily for decorative purposes.

Depolished glass is sandblasted, acid etched or ground; sometimes in patterns.

Rods are solid, clear or depolished, refracting light predominantly transversely, somewhat as ribbed or fluted glass.

Tubes are clear, or depolished inside or outside, thus providing several steps from flashing high lights to silvery sheen.

Colored glass contains the coloring matter within the glass.

Ceramic coated glass has a fired coating of white or colored, more or less diffusing material.

Cathedral glass covers a very wide classification of glasses sometimes obscured in no definite pattern, frequently tinted, variegated, or opalescent. A large group derives its texture from the presence of bubbles, "seeds," "strings," crackles, etc.

Molded glass includes sculptured grilles, plaques, etc., in pressed glass, often with diffusing finishes and colors. It is highly valuable for luminous detail. This class also embraces several types of structural glass.

Carved glass is any type of glass sandblasted in patterns of variable depth. It may be tinted or opaqued.

Antique glass is a glass of relatively smooth surface having a slight degree of nonuniform diffusion due to the intentional presence of bubbles, striae, fissures, etc.

Transparent glass falling under this classification has no apparent diffusing properties. Glasses are sometimes referred to as flint, crystal, clear.

Polished plate glass is one of which the surface irregularities have been removed by grinding and polishing, so that the surfaces are approximately plane and parallel.

Window glass is transparent, relatively thin, flat glass having glossy, fire-finished, apparently plane and smooth surfaces, but having a characteristic waviness of surface which is visible when viewed at an acute angle or in reflected light.

Structural glass includes pressed-glass building blocks, tile, etc., used in place of opaque materials. Blocks are made solid, hollow, and evacuated, embossed for decoration and scattering of light. They can be made in crystal or diffusing glass.

The term *mat* refers to the surface of a glass roughened by treatment with chemicals or mechanical means. The treatment adds to its diffusion properties as a result of refraction at the roughened surface. The term "cloudy" glass generally embraces opal, opalescent, alabaster, and similar glasses in which the diffusion results from the presence in the glassy matrix of myriads of tiny particles of different indices of refraction from that of the glassy matrix itself.

Many of the opalescent, alabaster, and ornamental glasses have roughened-in designs which are emphasized at night by the light transmitted from behind. The efficiency of transmission of ground or roughened glass is in general higher when the rough side is toward the light source.

The appearance of glass by day varies with its reflection factor. If a definitely white surface is desired opal glass should be used. The flashed opals, opalescent, and ground glasses assume progressively grayer tones.

Heat-absorbing Glass.—By the introduction of iron and other coloring materials glasses can be produced which have low transmission in ultraviolet and in infrared light and at the same time have a reasonably high selective, visible transparency. Ferric iron absorbs ultraviolet and ferrous iron is particularly adapted to the absorption of infrared radiation. Also each of these substances is weak in absorption in those regions where the other is strong in absorbing power. The control of the state of oxidation of the iron therefore determines the specific absorption properties of a given glass. Normally, of course, the iron present in any given glass is present as a mixture of the two states of oxidation, which precludes the maximum absorption in either region of invisible radiation. The residual color of the glass will depend on the preponderance of one oxide over the other to yield a blue-green, greenish, or yellow-green glass, depending on the relation of ferric to ferrous iron. If both are present in equal amounts the color will be green. If more than 50 per cent of the iron present is ferrous the resulting color will be blue-green, while if ferric iron predominates a yellowish-green color will be produced. Both of these oxides also absorb visible radiation. Therefore to produce a heat-absorbing glass for windows the total quantity of iron must be as low as practicable and the relative quantity of ferrous iron must be as high as practicable.

Transmission Data on Heat-absorbing Glass Made by the Pittsburgh Plate Glass Company

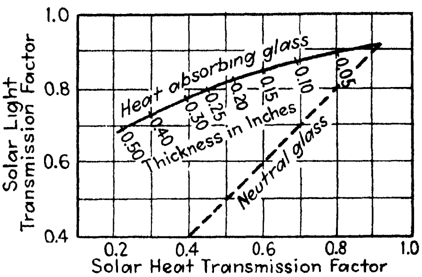
Thickness of sample 0.263 in. (6.68 mm.)

Source	Transmission Factor		
	Light	Heat	Infrared
The Sun	0.79	0 43$_5$	0 26*
Tungsten Lamp (C.T 2848°K)	0.75	0 26	0 24$_5$*
Tungsten Lamp (C.T. 2848°K)	0 78#	0 46**	

* Measured with light absorbing, heat transmitting filter.

\#Measured with filter converting 2484°K to mean sunlight.

** Measured with filter converting 2848°K to approximate solar energy.



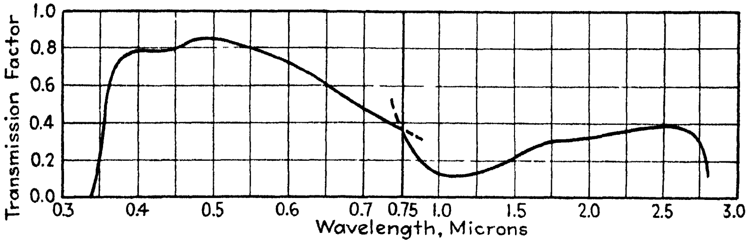


FIG. 2-19.—Test report on heat-absorbing plate glass. The total light- and heat-transmission factors for various sources are shown at the left. The complete spectrophotometric curve is shown below. The curve at the upper right relates the three quantities, light transmission, heat transmission, and glass thickness.

It has been experimentally determined that with the same general type of glass, melts of different color concentrations will have the same light transmission for the same heat transmission so that the different melts of glass can be plotted on the same curves. This relationship holds for glasses sufficiently dilute in coloring material as to be used for window glass.

Data on samples of heat-absorbing glass 0.25 in. thick are shown in Fig. 2-19.[1] It will be seen that glass of this thickness will transmit 79 per cent of the light and only about 43.5 per cent of the heat reaching it from the sun. The reason for this is shown by the spectral transmission curves, drawn in the lower part of the figure.

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[1] *Ibid.*, vol. 30, p. 403, 1935.

Thicker glass will absorb greater amounts of heat, as shown in the upper part of the figure. The dotted line would represent the performance of a neutral glass without selective heat-absorbing characteristics.

CHAPTER III

SOURCES OF LIGHT

NATURAL-LIGHT SOURCES

The sources of our natural illumination are the sun, the moon, and the stars.

The *sun* is approximately 93 million miles away, has a diameter of 865,000 miles and an intensity of approximately 2.3×10^{27} candle power. Its temperature has been estimated to be 6000°C. or more.

The *moon* is 240,000 miles from the earth, has a diameter of 2,160 miles and a candle power of 1.0×10^{17}. This is reflected light and the temperature is very low.

The *stars*, because of the great distances from the earth, produce little illumination, although the illumination from some, especially at certain times of the year, is appreciable. The temperature of some of the stars has been estimated to be approximately 50,000°C.

Daylight illumination is derived exclusively from the sun, and sunlight is greatly modified by the atmosphere. The sun's rays reach the earth's surface in varying proportions after selective reflection and absorption from minute particles in the atmosphere, from cloud masses, and from the surface of the earth. The changes which occur in sunlight in its transmission through the atmosphere are indicated by the averages of 6 months' observations (February to August, 1903) given in Table 3-1,[1]

TABLE 3-1.—ABSORPTION OF SUNLIGHT BY THE ATMOSPHERE

Wave Length, Microns	Percentage Transmitted
0.40	47.5
0.45	55.3
0.50	62.4
0.60	68.2
0.70	75.6
0.80	80.1

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[1] *Astrophys, J.*, vol. 19, p. 313.

which gives the average percentage of light of the different wave lengths, transmitted by the atmosphere, with the sun in zenith.

It will be seen that the red end of the sun's spectrum is reduced about 20 per cent by the influence of the atmosphere, while the violet end loses more than half of its initial intensity.

The increase in absorption of the sun's rays by the atmosphere as the sun passes from the zenith is considerable, as is shown by the difference in the intensity both of heat and of light when the sun is high in the sky and when it is near the horizon. It is also represented by the decrease in intensity both of light and of heat from summer to winter.

Intensity of Natural Illumination.—The values of the natural incident illumination of the earth vary from approximately zero for a dark moonless night with the sky heavily overcast to something like 13,000 foot-candles for the normal intensity and 10,000 foot-candles for the horizontal illumination due to direct rays from a noonday sun with the sky clear.

With a full moon the maximum normal and horizontal intensities during the night in a case studied were 0.0388 and 0.0216 foot-candle, respectively. The rate of increase during the hour preceding sunrise is surprising. The intensity at about 7 min. before sunrise was approximately 10,000 times that at 1 hr. previous. At about 25 min. before sunrise and 25 min. after sunset the illumination was approximately 2 foot-candles. It was also found that certain cloud formations have the effect of increasing the intensity of illumination by diffusion, while other clouds act as absorbing media and reduce the illumination intensity. Variations in illumination intensity due to clouds are often of a large order and sometimes occur suddenly, but in the absence of clouds the rate of change of intensity between an hour after sunrise and an hour before sunset is regular. During the hours of dawn and twilight the rate of change of intensity is very high.

In Fig. 3-1 are curves showing the variation of natural illumination through the day for three periods of the year. The latitude is approximately that of Chicago or Boston—42° N. Curves 1, 2, and 3 refer to the horizontal illumination from both sun and sky on a clear day, while curves 4, 5, and 6 refer to the illumination from a clear blue sky only. It will be noted that these data are for the longest, shortest, and average days of the year.

In Fig. 3-2 are shown curves for the same dates as before, based on a sky so densely clouded that the position of the sun could not be determined. The average sky, with thin clouds or haze, or scattered white clouds, produces about twice this illumination.

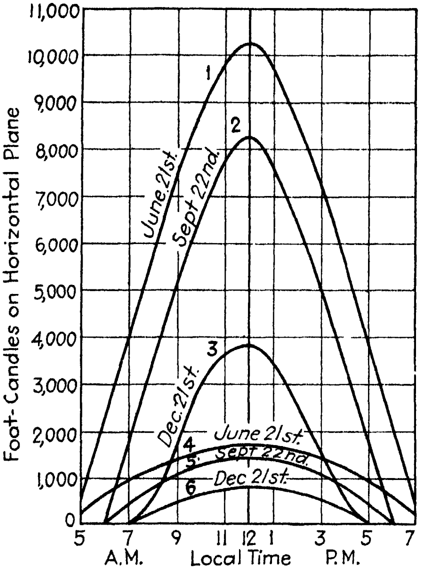

FIG. 3-1.—Diurnal variation in daylight illumination. Cloudless sky. Latitude 42° North. Curves 1, 2, and 3 represent illumination due to both sun and sky. Curves 4, 5, and 6 refer to illumination from a clear sky only.

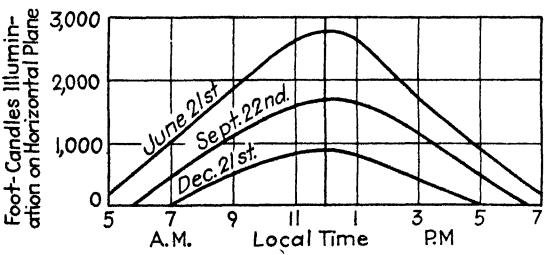

FIG. 3-2.—Diurnal variation in daylight illumination. Latitude 42° North Sky so densely clouded that position of sun could not be seen.

Sunlight and Skylight.—The proportions of our natural light coming from the sun and from the sky vary greatly. At low elevations and in the middle of the day with a clear sky as much as one-sixth of our light may come from the sky and five-sixths direct from the sun. At observatories high in the mountains on very clear days it has been found that as little as one-tenth of the light which reaches the earth comes from the sky and nine-tenths comes directly from the sun.

Light clouds will increase the amount of diffused light and decrease the amount of direct light, thus varying the ratio. Cumulus sunlit clouds are much brighter than a clear blue sky even if the latter be hazy. The amount of light received from such a sky may be as much as one-third to two-fifths of the total light received from the sky and sun together with the sun visible.

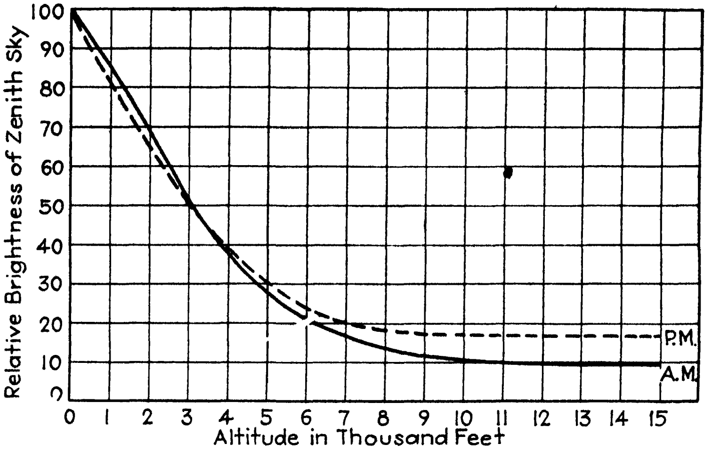

FIG. 3-3.—Variation of brightness of zenith sky with altitude of measurements, on a very hazy but cloudless day.

With the sky completely overcast with white clouds the light received from the clouds may equal that received from the sun. The light from a clear blue sky does not vary greatly in intensity during a considerable portion of the day. The amount of direct light from the sun falling upon a horizontal plane, however, varies from practically zero at sunrise and sunset to a maximum at noon.

At very high altitudes the sky is a very dark blue and contributes only about 5 per cent of the total light at an altitude of 3.5 miles.

On a hazy but perfectly cloudless day measurements[1] of the brightness of zenith sky from the earth's surface to 15,000 ft. show that the brightness of the sky decreases enormously with the altitude. The results are shown in Fig. 3-3. The point where the curve flattens out indicates the altitudes where the earth haze ends, or about 10,000 and 7,000 ft. for morning and afternoon, respectively.

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[1] *J. Franklin Inst.*, vol. 187, pp. 289, 409, 1919.

Reports by Capts. Stevens and Anderson of the 14-mile altitude flight into the stratosphere indicate almost total blackness above that level, except, of course, toward the sun.

Average Daylight.—That average daylight should be accepted as a standard, in terms of which the color values of the existing sources of artificial illumination may be compared, seems to have a sound philosophical basis. The maximum of the luminosity curve of the normal eye is in the same region of the spectrum as the maximum of the radiant energy of sunlight. The organs of vision have for ages been developed for the most part in daylight, and they are accustomed to light which possesses the spectrum of natural illumination. It seems only reasonable and rational therefore that the color values of illuminants should be expressed in terms of the components of average daylight.

If daylight is defined as the natural light illuminating a shaded surface, this is by no means a light of constant spectral relations. Its components will be different in different parts of the world, at different times of the year, at different times of the day, and under different atmospheric conditions.

Of the indirect components of daylight, the light from the cloudless sky is relatively richer in blue and violet and weaker in red rays than is sunlight by greatly varying amounts, which depend upon the state of the atmosphere. Daylight composed of the direct rays from the sun and the indirect rays from the sky will differ but little, however, from sunlight, since sunlight is by far the dominant factor. Skylight, on the other hand, will be much bluer, since the direct rays of the sun are intercepted. There is also a great difference in sunlight at different times of the year and at different times of the day. Of the different kinds of daylight the two most definite are the light from a *clear blue zenith sky* and *noon sunlight*, with a clear atmosphere.

By reducing the available spectrophotometric determinations of sunlight and skylight of radiant energy, Ives[1] found that:

1. Clear noon sunlight in summer corresponds closely to the energy determinations of a black body at 5000° abs.

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[1] *Trans. Illum. Eng. Soc.*, vol. 5, p. 189, 1910.

2. Clear blue skylight averages twice as much energy in the blue (0.450μ) as does sunlight for equal intensity in the yellow (0.590μ).
3. Light from cloudy skies varies from near blue to sunlight.
4. The light from the sun at low altitudes shows a deficiency in blue similar to the excess in blue of the clear sky.

Because of the above variations in daylight Ives suggested that the best way to arrive at an acceptable value of average daylight is to take advantage of the coincidence above stated between the maximum of sensibility of the eye and the maximum of the sun's energy as it reaches the earth through the atmosphere. Moreover, if this is not merely a coincidence but the result of adaptation, there is a criterion of average daylight which is more exact than could be obtained by any number of series of daylight measurements. Since this adaptation exists the inference is that the most probable average daylight is the light whose spectral maximum falls in the region of maximum sensibility. This corresponds to *clear noon summer sunlight,* which is the most efficient daylight and which agrees closely with the visible radiation of a black body at 5000° abs. Since the eye permits considerable variation in the hue of light and still gives the sensation of "white" light, the terms "average daylight" and "white light" may be used interchangeably.

ARTIFICIAL-LIGHT SOURCES

The sources of artificial light discussed in this text are the incandescent, arc, gas, and vapor lamps.

Incandescent Lamps.—The first commercial incandescent lamp appears to have been produced by Edison in 1879. The filament consisted of carbonized paper. Later filaments of carbonized bamboo were used and these were later improved by coating with a hydrocarbon. In 1893 a process of making a cellulose filament from absorbent cotton dissolved in zinc chloride was discovered. The solution had the consistency of thick molasses and was forced through a die, in the form of fine thread, into an alcohol bath, which hardened it.

This filament was of uniform constitution and size and, after being carbonized, formed a filament of remarkable strength and flexibility. After mounting in the bulb, the filament was heated by passing an electric current through it while in the presence of a hydrocarbon vapor. This vapor was decomposed and carbon deposited upon the filament, forming a smooth, dense coating and correcting for any lack of uniformity that might exist. This lamp produced about 3.3 lumens per watt.

The *Gem* or *metallized* carbon-filament lamp was put on the market in 1905. The filament of this lamp was made by heating a treated carbon filament to the high temperature of the electric furnace. This treatment changed the temperature coefficient of resistivity from negative to positive—hence the expression "metallized" carbon filament. This lamp gave 4.0 lumens per watt.

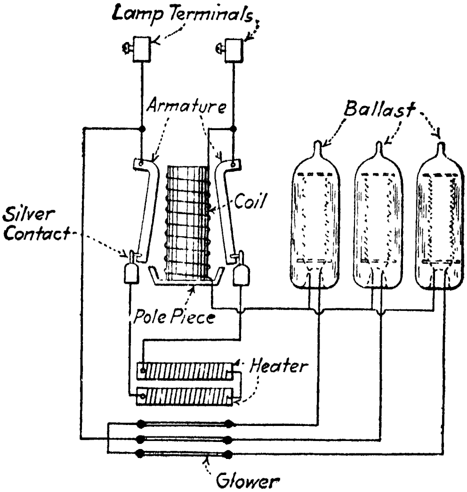

FIG. 3-4.—Three-glower Nernst lamp.

The *Nernst lamp*, a German invention, came into commercial use in this country in 1900. It possessed a "glower," heater, "ballast," and cutout (Fig. 3-4). The glower consisted mainly of zirconium oxide and operated in the open air. It was a non-conductor when cold, so had to be heated before current would pass through it. This was accomplished by an electric heating coil, made of platinum wire, located just above the glower. As the glower became heated and current passed through it, the heater was automatically disconnected by an electromagnet cutout.

The glower had a decided negative temperature coefficient, so a steadying resistance or ballast was put in series with it. This consisted of an iron wire mounted in a glass bulb filled with hydrogen gas. Iron has a positive temperature coefficient of resistivity which is very marked at the temperature at which the ballast was operated.

The lamp operated on 220-volt alternating-current circuits. The glower consumed 0.4 amp. One-, two-, three-, four-, and six-glower lamps were made, consuming 88, 196, 274, 392, and 528 watts, respectively. The multiple-glower lamps were more efficient, owing to the heat radiating from one glower to another. Their efficiencies were from 3½ to 5 lumens per watt and their average candle power throughout life was about 80 per cent of initial. The lamp disappeared from the market about 1912.

The *osmium lamp* was commercially introduced in Europe in 1905. It had a very fair maintenance of candle power during its life, and an average efficiency of about 5 lumens per watt. Osmium is a very rare and expensive metal, usually found associated with platinum, and therefore difficult to obtain. The lamp was extremely fragile.

The *tantalum lamp*, having a filament of tantalum, a ductile metal, had an initial efficiency of about 5 lumens per watt. When used on alternating-current circuits the filament crystallized and a shorter life resulted than on direct-current circuits. It was on the market from 1906 to 1913.

Tungsten-filament Lamps.—The tungsten-filament lamp became commercially available in this country in 1907. The filaments were made by mixing finely divided tungsten powder with a binder to form a paste, and then squirting the paste through a die, producing a thread. Hairpin loops of this thread were treated to remove the binder and several of them were mounted in series within the bulb to give the necessary resistance. The lamp was fragile, but could be operated at 7 lumens per watt.

A process of making tungsten ductile was discovered by Coolidge about 1911. This made possible a continuous uniform filament of drawn ductile tungsten, simplified the manufacture of the lamp, and very materially increased its ruggedness and efficiency.

Research by Langmuir made it possible to greatly increase the efficiency of the tungsten lamp by the use of an inert gas in the bulb. Lamps of this type were produced commercially in

1913. These are known as the type C lamps, to distinguish them from the vacuum or type B lamps.

The current passing through a filament and the temperature at which it is to operate are dependent upon the diameter of the filament. A tungsten filament of large diameter can be operated at a higher temperature than one of smaller diameter, as a greater amount of filament material can evaporate without reducing its diameter to as great an extent, and, as previously stated, a filament can be operated in gas at a higher temperature than in a vacuum.

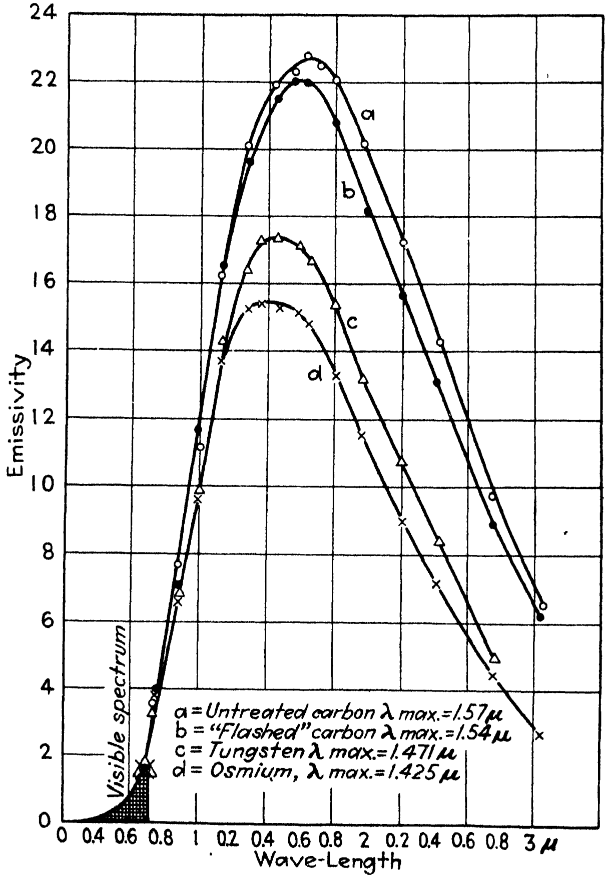

FIG. 3-5.—Radiation curves for incandescent lamps.

The relation of *visible to total radiation* of incandescent electric lamps is shown graphically by the energy curves derived by Coblenz and Hyde[1] and shown in Fig. 3-5. These curves refer to lamps having filaments of untreated carbon (curve *a*), flashed carbon (curve *b*), tungsten (curve *c*), and osmium (curve *d*). The visible radiation is indicated by the shaded portion and extends from 0.4 to 0.7μ. The lamps were so operating that the amount of visible radiation was the same for each. It will be seen that the less invisible radiation from the metal-filament lamps indicates a higher efficiency for these sources. It will also be seen that the maxima of the energy curves shift with these indications of increase in efficiency in the same direction as the maxima of the black-body radiation curves with increase of temperature. These curves also show the effect of selective radiation. Untreated carbon is very close to a black body. Tungsten behaves like a gray body in the visible region while in the longer wave lengths its emission is less than if it were truly "gray."

Inert Gas.—It was found that inserting an inert gas into the incandescent-lamp bulb decreased the evaporation of the filament and lengthened its life. The gases found best suited for this purpose were nitrogen and argon. The evaporation of the filament is less in argon gas, and the lamp can operate at a higher efficiency for the same filament life with a considerable amount of argon present instead of all nitrogen, as in the case of the earlier gas-filled lamps. The reason is based on the theory of gases. The conduction losses in gas are proportional to the velocity of the molecules of the gas. The velocity of the molecules of a gas at a certain temperature is inversely proportional to the square root of their atomic weights. Since the molecular weight of argon is 39.8 and that of nitrogen is 28.0 the reason for the use of the argon gas is obvious. The low arcing potential of the argon gas, however, made necessary the admixture of some nitrogen with the result that the standard gas-filled lamp contains about 85 per cent argon and about 15 per cent nitrogen.

The gas, however, conducts so much heat from the filament that a concentrated filament realized in the tightly wound helical construction was necessary in order to secure the greater efficiency. The coiled filament is, in this way, less exposed to the circulating gases, the turns supply heat to each other, and the filament is mechanically stronger.

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[1] *Bur. Standards Bull.*, vol. 5, p. 339, 1909.

Characteristics of the Tungsten Lamp.[1]—Since lamps are rated to give a certain length of life (1,000 hr. for the standard multiple lamp) it is obvious that the larger and more efficient lamps must have larger filaments. The cross section of a filament which determines the current rating of a lamp varies with the square of the diameter, and the radiating surface coming in contact with the gas varies directly with the diameter. A consideration of these facts makes obvious the reason for the higher efficiency of the lamps of larger current rating and explains why the small-wattage 110-volt lamps are still of the vacuum type even though the helical filament construction is used. In general, a lamp with a filament current of less than 0.3 amp. is more efficient in the vacuum type.

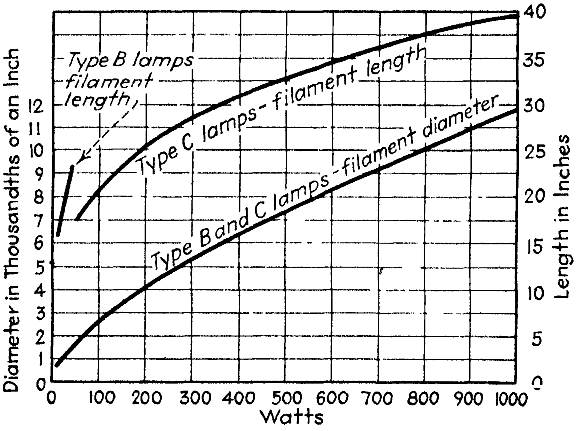

FIG. 3-6.—Filament dimensions of 115-volt Mazda lamps.

Tungsten wire can be drawn to a diameter of 0.0004 in. or approximately one-sixth the diameter of a human hair. The lengths and diameters of filaments for standard 115-volt lamps are indicated in Fig. 3-6.

The efficiencies of lamps increase with the rated wattage. This is due to the decreased heat loss in percentage of the total wattage of the lamp and also to the ability of larger filaments to withstand higher operating temperatures. The efficiencies in lumens per watt for sizes up to 1,000 watts are indicated in Fig. 3-7.

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[1] "Theory and Characteristics of Mazda Lamps," *Gen. Elec. Co. Bull.* L. D. 114-D.

The lumens output of a constant-potential lamp decreases gradually during its life. As the lamp burns the filament slowly

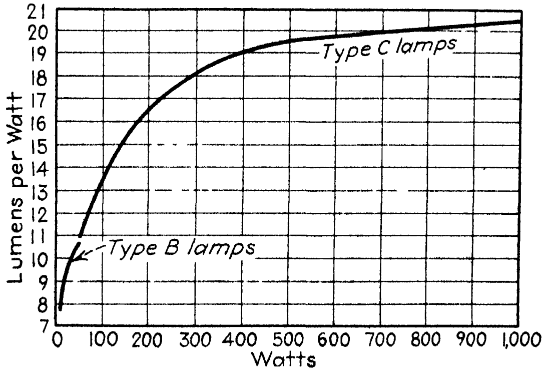

FIG. 3-7.—Efficiencies of 115-volt Mazda lamps.

evaporates and becomes smaller in cross section and of higher resistance, taking less current and producing less light. Also the material evaporated from the filament is deposited on the bulb and absorbs some of the light. These effects are shown by the performance curves in Figs. 3-8 and 3-9.

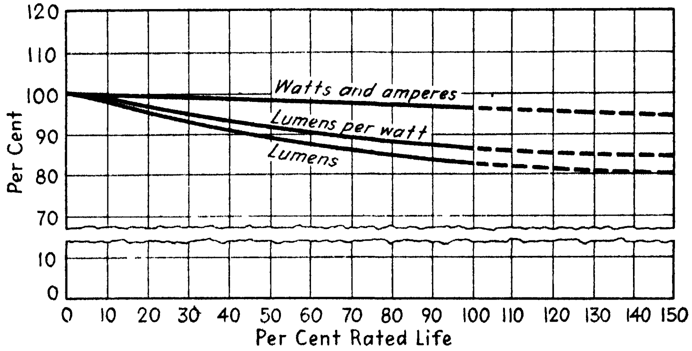

FIG. 3-8.—Typical operating performance of small multiple Mazda lamps.

Although lamps are rated for a certain length of life, it should be understood that this is the average life. Some may fail before the allotted span, while others may continue away beyond the expected life. Characteristic curves for tungsten lamps for variation in voltage are shown in Figs. 3-10 and 3-11. Special notice is called to the variations in lumens and life of the lamp. A decrease of 10 per cent in voltage reduces the light output 30 per cent. An increase of 10 per cent in voltage will cut the average life to approximately 30 per cent.

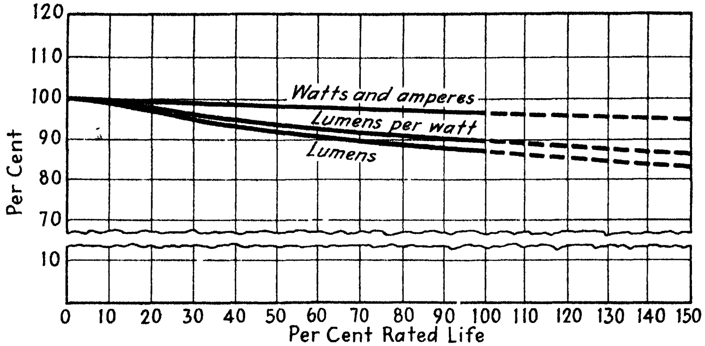

FIG. 3-9.—Typical operating performance of large multiple Mazda lamps.

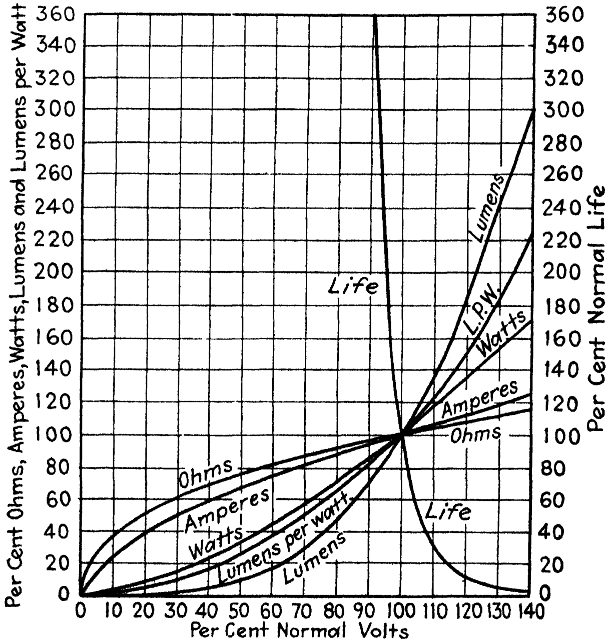

FIG. 3-10.—Ampere, watt, lumen, efficiency, and life characteristics of Mazda lamps on varying voltage.

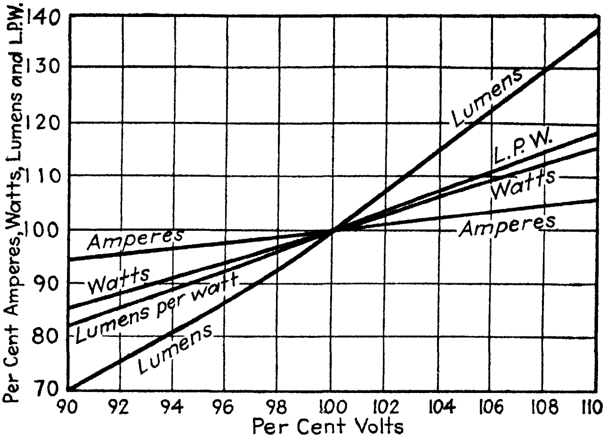

FIG. 3-11.—Characteristic curves, large multiple Mazda lamps.

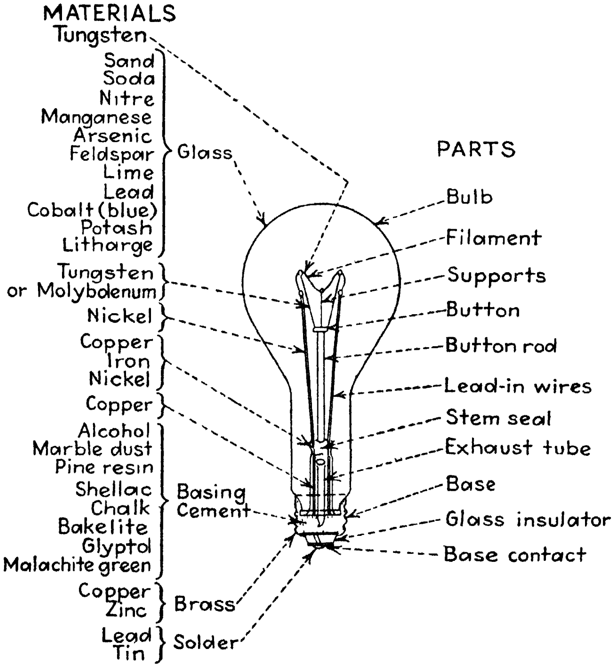

FIG. 3-12.—A large variety of raw materials enter into the structure of the several parts of the incandescent lamp, the nomenclature of which is indicated.

More accurate values of tungsten-lamp performances may be calculated using the following exponential relations:

The output in lumens from standard Mazda lamps is given in Table 9-3, Chap. IX.

The names of the parts of a tungsten lamp and the materials of which each part is made are shown in Fig. 3-12.

Exponents of Lamp Characteristics.—The watts, lumens, lumens per watt, life, etc., at other than normal values can be calculated by means of the following relations:

$$\frac{w}{W} = \left(\frac{v}{V}\right)^a, \quad \frac{f}{F} = \left(\frac{v}{V}\right)^b = \left(\frac{w}{W}\right)^c, \quad \frac{E}{e} = \left(\frac{V}{v}\right)^d = \left(\frac{F}{f}\right)^e,$$

$$\frac{l}{L} = \left(\frac{V}{v}\right)^f = \left(\frac{F}{f}\right)^g = \left(\frac{E}{e}\right)^h$$

where W = watts
V = volts
F = lumens
E = lumens per watt
L = life of the lamp

the capital letters indicating normal values and the small letters those other than normal. The values of the exponents are as follows:

Lamp	*a*	*b*	*c*	*d*	*e*	*f*	*g*	*h*
Type *C*........	1.54	3.38	2.19	1.84	0.544	13.1	3.86	7.1
Type *B*........	1.58	3.51	2.22	1.93	0.550	13.5	3.85	7.0

If the light emitted by a 100-watt type C lamp at rated 120 volts is 1,320 lumens, then when operated at 110 volts it would be

$$1{,}320 \times (110/120)^{3.38} = 984 \text{ lumens}$$

Rating of Incandescent Lamps.—From an engineering point of view a lamp should be so rated as to make the cost of lumen-hours a minimum. The cost involves the cost of lamp, cost of electrical energy, and the intangible element, inconvenience of lamp renewal. This element of inconvenience plays a considerable part, with the result, which seems to be satisfactory to all concerned, that for lamps of common usage under customary average conditions a standard average life of 1,000 hr. has been adopted. For special types of lamps shorter or longer standard-life values have been adopted depending upon the requirements of each particular service (see Table 3-2).

TABLE 3-2.—STANDARD AMERICAN LAMP LIVES FOR VARIOUS CLASSES OF SERVICE*

Class of service	Range of voltage	Standard life, hr.
Traffic signal	100 to 130	1,500
Street-railway lamps	100 to 130	1,500
10- and 15-watt sign lamps	100 to 130	1,500
Street series lamps	†	1,350
Multiple lamps for standard lighting service	28 to 300	1,000
Floodlighting lamps	100 to 130	800
Decorative lamps (medium base)	100 to 130	750
Decorative lamps (intermediate and candelabra base)	100 to 130	600
Airport floodlighting lamps (1,000 watts)	100 to 130	500
Locomotive headlight lamps	32	500
Spotlight lamps	100 to 130	200
Airport floodlighting (1,500 to 10,000 watt lamps)	32 and 115	100
Projection lamps	50 and 115	50

* LIEB, *Trans. Illum. Eng. Soc.*, vol. 25, p. 637, 1930.
† Series burning lamps rated at 3.5 to 20 amp.

Incandescent-lamp bulbs may be "clear," "inside frosted," "clear colored," and "diffuse colored."

Frosting the bulb greatly reduces the brightness of the lamp. The inside frosting offers two advantages: (1) the outside of the bulb is smooth and will gather less dirt than a roughened surface; (2) with the diffusing medium on the inside less light is lost than where the rays pass back and forth through the glass in the diffusing process of the outside frosting. The effects of these treatments compared with the clear lamp are shown in Table 3-3.

Frosting may be done by an acid-etching process. Acid etching produced sharp angular crevices on the surface of the glass. This caused the bulb to weaken when the frosting was on the inside and the bulbs of such lamps were easily broken. A special fortifying treatment, which rounds out the bottoms of the crevices, restores the strength of the glass.

TABLE 3-3.—APPROXIMATE LIGHT OUTPUT OF ETCHED AND COLORED LAMP BULBS, WHEN NEW*

Treatment	Percentage of Output of Clear Glass Lamps
Inside frosted	98 to 99
Outside frosted	94 to 96
Natural colored glass:	
Blue	1
Red	8
Green	12
Amber	70
Inside colored:	
Ivory	75
Yellow	65
Flame tint and amber orange	40
Green	3
Red	2
Blue	1
Blue glass bulbs (so-called daylight lamps)	65

* *Trans. Illum. Eng. Soc.*, vol. 25, p. 637, 1930.

Transient Characteristics.—Tungsten has a positive temperature coefficient of resistivity. The result of this is that the initial current is several times normal. The candle power does not "overshoot," as some think, this being merely an optical illusion, but rises continuously to its steady value. These relations are shown in Fig. 3-13.[1]

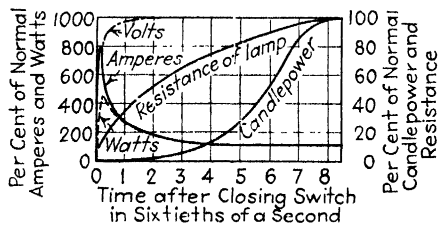

FIG. 3-13.—Transient characteristic of tungsten lamps on direct current.

Flicker Effect.—In all classes of illumination a flickering light should be avoided, since the iris cannot keep pace with the rapid fluctuations and too little and too much light falling alternately upon the retina causes fatigue. This condition is familiar to all who have endeavored to read by the light from an open gas flame or a 25-cycle arc lamp. It has been found that if repeated stimuli succeed each other within their period of persistence the sensation will be that of continuous light, but when the interval between the stimuli is nearly equal to the time of dying away of a sensation the light will appear to flicker. The frequency at which the flicker from an alternating source cannot be detected varies with the temperature of the luminous source, the thermal capacity of the radiator, and with the intensity of illumination of the object viewed.

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[1] *Standard Handbook for Electrical Engineers*, p. 1656, 6th ed., 1933.

The flicker effect is less with lamps of large filaments. It is also less at lower illumination intensities and greater when the light enters the eye at a considerable angle from normal and falls on the outer portions of the retina. The flickers of tungsten lamps of different sizes for various frequencies are shown in Fig. 3-14.[1] It is known that no flicker is noticeable on 60 cycles even with a small lamp, hence by referring to these curves it will be seen that a large lamp on a 25-cycle circuit should be satisfactory.

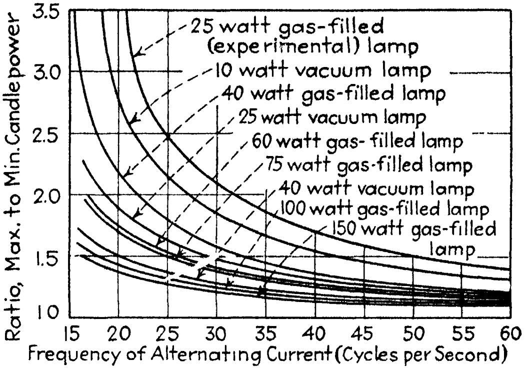

FIG. 3-14.—Flicker of tungsten-filament lamps on alternating currents.

Characteristics of Series Incandescent Lamps.—Since the resistance of tungsten increases with temperature, changes in voltage produce lesser, while changes in current produce greater, variations in watts, lumens, efficiency, etc., than if the resistance remained constant. It is therefore desirable that a series circuit have close regulation as a given percentage in current is the equivalent of nearly double the same percentage variation of voltage in a multiple circuit.

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[1] *Ibid.*, p. 1654, 1933 ed.

The characteristic curves of the series tungsten lamp are indicated in Fig. 3-15. One per cent change in current will produce about 1.75 per cent change in voltage, about 2.75 per cent change in wattage, about 7 per cent change in lumens, about 3.5 per cent change in lumens per watt, and 24 per cent change in life.

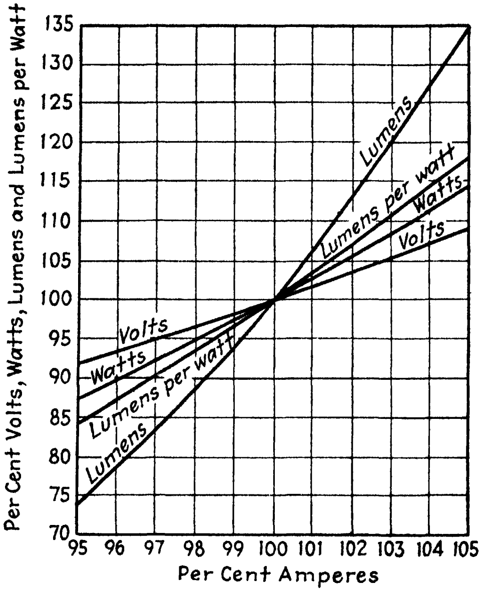

FIG. 3-15.—Characteristic curves of series Mazda lamps with variation in amperes.

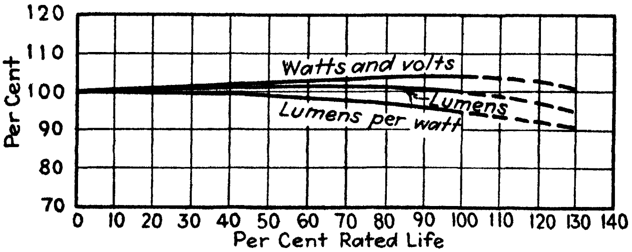

FIG. 3-16.—Typical operating performance of high-current Mazda street series lamps.

The life performance on a constant-current series circuit is quite different from that on a constant-voltage multiple circuit. On series circuits the increase in resistance during life due to the evaporation of the filament causes the wattage taken by the lamp to increase because the current in the circuit is maintained constant. On a multiple circuit the wattage decreases. The increasing wattage during life on a series circuit causes an increase in temperature of the filament, which causes the lumens, produced by the filament itself, to increase. The opposite is true on a multiple circuit. There is a darkening of the bulb on both types of circuit. Therefore the lumen maintenance of a lamp on a series circuit is dependent upon the difference between the increase in lumens produced by the filament and the absorption due to the darkening of the bulb. The lumen maintenance is better on series than on multiple circuits. In the large-size lamps there is no increase in lumens during life. The increase in voltage and wattage of the series lamps will amount to about 4 per cent at the end of their rated life. Life performance of series street lamps is shown in Figs. 3-16 and 3-17.

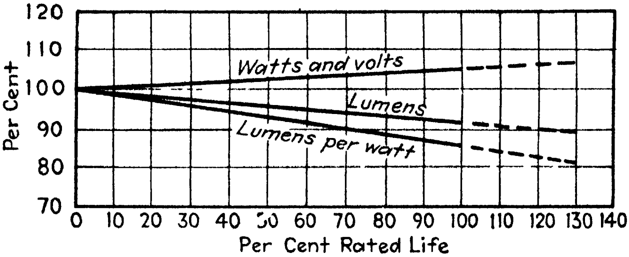

FIG. 3-17.—Typical operating performance of low-current Mazda series lamps.

Special Lamps.—The *sunlight lamp* is the result of an effort to produce ultraviolet radiation in quantities approximating that of sunlight. The lamp has a tungsten filament (for starting), a pair of electrodes, and a small amount of mercury in a bulb of special glass, which transmits the ultraviolet radiation. It is a low-voltage lamp and requires a transformer for its operation. The transformer is furnished as a component part of the equipment. The latter takes the form of a portable lamp and can be plugged directly into the lighting circuit. When the circuit is closed the starting filament heats and vaporizes some of the mercury. An arc is then established between the two electrodes and that arc in the mercury vapor becomes the source of the ultraviolet radiation. Reflectors should be used with these lamps to increase their effectiveness. The reflectors should be of either aluminum or chromium as other materials absorb rather than reflect ultraviolet energy. The construction of the lamp is shown in Fig. 3-18.

The *daylight lamp* has a blue glass bulb which absorbs much of the yellow rays and transmits light approaching daylight in color values. The absorption of the blue glass is about 35 per cent.

The *moonlight lamp* consuming 3 watts for the nursery, bedroom, bath or hall is interesting. The filament is so small that it cannot be drawn through diamond dies according to the usual practice. The filament is drawn to about 6-watt size. It is then placed in a molten solution of potassium nitrate and nitrate to reduce it to the desired size, which is about 0.0003 in. in diameter.

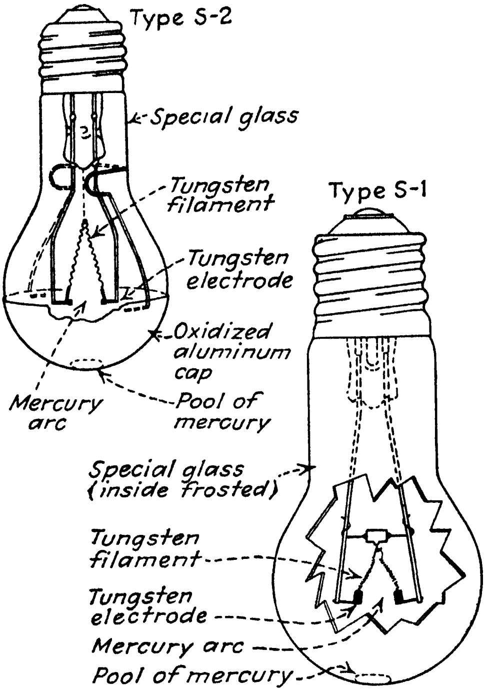

Fig. 3-18.—The sunlight lamp.

The *lumiline lamp* is a tubular lamp with a filament running lengthwise through it. Contact is made at the ends through special supporting sockets. By the use of these lamps practically continuous lines of light may be installed in narrow spaces. They are made in several colors.

The *three-light lamp* (Fig. 3-19) contains two filaments, each of which may be burned either singly or in combination with the other, thus providing three different levels of illumination from a single lamp bulb. These lamps are equipped with a mogul screw base which has an additional center contact in order to permit separate control to each filament. A special socket is necessary to accommodate this new base.

The *Photoflood lamp* was designed for photographic lighting. It is a high-efficiency lamp so rated that its life is short. A small unit resembling a 60-watt inside-frosted lamp but having a photographic effectiveness equal to that of a 750-watt standard lamp has a life of about 2 hr. A larger commercial unit has a life of about 10 hr.

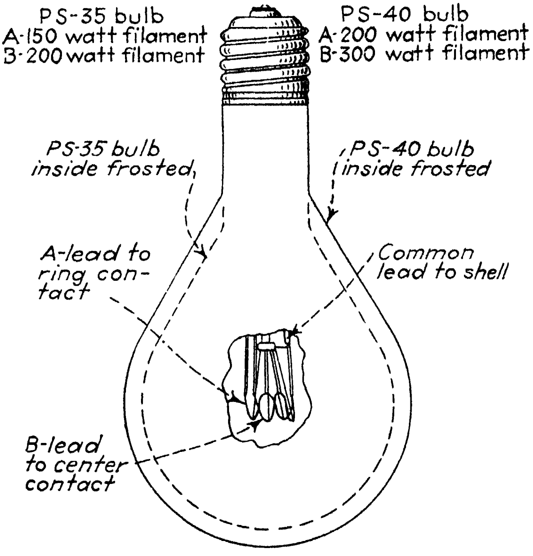

FIG. 3-19.—Three-light Mazda lamp.

A *movieflood lamp* for motion-picture photography consumes 2,000 watts, gives 68,000 lumens, and has a life of about 15 hr.

The tendency for high-candle-power, high-efficiency lamps like the movieflood lamps to blacken during operation has been remedied by placing a cleaning powder inside the lamp. This acts as a cleaning agent. A few swishes of the powder removes the discoloring. Many of the high-wattage lamps have this tungsten cleaner in the bulb.

The *Photoflash lamp* consists of a bulb filled with crumpled aluminum foil in an atmosphere of oxygen. It has a low-voltage filament for starting the flash which can be operated from a small flashlight battery or house voltage. The small amateur lamp has a peak output of about 2½ million lumens. The large lamp for professional work gives a maximum intensity of about 17½ million lumens. This latter figure is approximately equivalent to the light from one thousand 1,000-watt lamps. The duration of the flash is about 0.02 sec. A well-designed reflector will increase the effectiveness of the flash several fold especially out of doors or in rooms having dark walls and ceilings.

Arc Lamps.—The first arc lamps used for street lighting had long electrodes of carbon and were of the open-arc type. These date, commercially, from about 1878. The electrodes were rapidly consumed, lasting from 8 to 16 hr., depending on their size and length. About 1893 it was found that by placing a tight-fitting globe about the arc the life of the carbons was increased ten to twelve times owing to the restricted amount of oxygen admitted to the hot carbon tips. This lamp replaced the open arc and was used extensively on the series systems of lighting.

The *flame arc lamp* was produced by Bremer in Germany in 1898. The electrodes consisted of carbons impregnated with calcium fluoride. These lamps were high-candle-power units, giving a brilliant yellow light which came from the arc flame. Two flame arc lamps were operated in series on 110-volt circuits. They consumed 550 watts each, giving an efficiency of about 35 lumens per watt on direct current and about 30 lumens per watt on alternating current.

The use of barium salts in the carbon gave a white light with an efficiency of 18 and 15 lumens per watt on direct and alternating currents, respectively. By using strontium salts in the carbons, a red light was obtained at a considerably lower efficiency.

Flaming arc lamps were remarkably efficient, but their maintenance expense was high. Later, about 1908, enclosed-flame arc lamps were made which increased the life of the electrodes.

The *luminous* or *magnetite arc lamp* owed its origin to the chemical research of Steinmetz in an endeavor to produce an arc lamp more efficient than the preexisting types and at the same time having a life for its electrodes comparable with those of the enclosed-arc lamp. The material of the cathode, as finally adopted, consisted of magnetite and titanium oxide. The magnetite particles make the arc stream a good conductor, but they are not very luminous; consequently the titanium oxide is introduced to furnish luminescence.

It was found that the magnetite was consumed faster than was necessary to produce the same efficiency and a small amount of chromium was introduced, which has a higher melting point than magnetite, although it is similar chemically. This restrained the molten magnetite and retarded the consumption of the electrode.

The luminous intensity of the lamp was due to the incandescent particles of titanium supplied by the cathode and carried into the arc stream by the electric current. As a result of this phenomenon, the negative electrode was the only one consumed, if the anode, which was of copper, was of sufficient size to conduct the excessive heat and not reach the evaporization temperature. If the anode was of too great size the material from the cathode would condense upon it; therefore the approximate dimensions of the positive electrode were determined from these two considerations. The spectrum of the arc showed the characteristics of the material of the cathode and was not affected by the constituents of the anode. With the magnetite-titanium cathode the light emitted was of intense brilliancy and whiteness.

The arc burned in the open air at about 75 volts. The magnetite electrode had a life of about 350 hr. The 4-amp. lamp had an efficiency of 11½ lumens per watt. A high-efficiency 4-amp. electrode, having a shorter life, gave 17 lumens per watt. A 6.6-amp. lamp was also made, giving about 18 lumens per watt with regular electrodes.

The luminous arc lamps required direct current for their operation, and were generally supplied by constant-current transformers through mercury-arc rectifiers.

Carbon arcs using cored carbons, the core being filled with rare-earth oxides, iron, nickel, etc., emit considerable ultraviolet radiation which in combination with their characteristic cyanogen band at about 389 millimicrons has made possible the projection of ultraviolet radiation in useful intensities at distances of more than a few feet.

The greater convenience and simplicity of the tungsten-filament lamp have caused it to generally displace the arc lamp for street lighting service. The use of arc lamps is now largely confined to photochemical work, to projection work where the high intensity of the crater is desirable, and to large-wattage units as used in searchlights.

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CHAPTER IV

GAS AND VAPOR LAMPS

While the tungsten-filament lamp surpasses all its predecessors as to efficiency it seems evident that further large increases in efficiency will have to come from gaseous sources, either true gases or the vapors of material ordinarily liquid, *e.g.*, mercury, or a solid, *e.g.*, sodium.

Vapor Lamps.—Gases and vapors can be made luminous by passing an electrical discharge through them. The color of the light produced by the discharge depends upon the nature of the gas or vapor. The increase in discharge current merely increases the intensity of the light and does not materially change its color. Also the intensity or candle power of the light depends upon the nature of gas or vapor. In other words, vapor lamps are luminescent-light sources and not dependent on temperature for higher efficiencies.

The first gas and vapor lamps were of the cold-cathode type. There was a large consumption of energy at the cathode which yielded no light and greatly decreased the efficiency. There was also a mechanical disintegation of the cathode supposed to be caused by the positive ions striking the cathode with a high velocity due to the large potential drop at the cathode. This disintegration or "sputtering" caused a blackening of the tube. The high cathode drop also caused a cleanup of the gas increasing the "resistance" of the tube during operation. In the Moore tube lamp provision was made for renewing the supply of gas, while later types of lamps overcame this objectionable feature. To reduce the cathode energy loss and reduce sputtering a low current density at the cathode was used.

As a result of the high cathode drop it was impossible to produce a low-voltage lamp. To have reasonable efficiency it was necessary to make long tube units so that the cathode drop would be small compared with the total voltage of the tube.

If the cold cathode is replaced by a hot cathode capable of emitting electrons in sufficient number to supply the discharge current, the cathode drop will be reduced to a value only slightly in excess of the ionizing potential of the gas.

Moore tube lamp is of the cold-cathode type and represents the result of some 12 years of persistent research on the part of Moore. It involved the principle of the Geissler tube with small amounts of gas to modify and increase the amount of light. In the usual form it involved a continuous glass tube 1.75 in. in diameter and 40 to 200 ft. in length. Nitrogen gas gave a yellow light and the greater efficiency; a 200-ft. tube gave about 10 lumens per watt. Carbon dioxide gas gave a white light at about half the efficiency of nitrogen.

The carbon dixoide tube, on account of its daylight color value, made an excellent light for color matching. A short tube lamp is made for this purpose; it is the only use the Moore tube now has, owing to the more efficient and simpler modern lamps.

Neon-gas Lamp.—There are two general types of this lamp, *viz.*, the cold-cathode and the hot-cathode types.

The *cold-cathode* neon-tube light source is similar in principle to the Moore tube unit. The ionization potential of neon is much less than that of the common gases, *e.g.*, nitrogen and carbon dixode, less than that of helium but more than that of argon, krypton, or xenon. Its luminous orange-red color has made it popular with the public for advertising signs and spectacular effects.

Neon tubes for sign lighting are seldom made larger than 1.5 cm. or smaller than 0.7 cm. in outside diameter. In general, the smaller the tube the more brilliant the light. The voltage per foot for the 1.5-cm. tube is about 125 volts and for the 0.8-cm. tube about 260 volts.

The pressures used in neon tubes range from 3 to 20 mm. The current and the luminous intensity of the tube will increase as the voltage is increased and also as the pressure is decreased down to about 3 mm. The value of current is something less than 75 milliamp.

Argon, because of its extremely low ionization potential, is used with other gases and with vapors as the "carrier" gas to assist in starting the electrical discharge and is especially desirable in the cold-cathode tubular lamps. It is mixed with neon in the sign lamps in the ratio of about 80 per cent argon to 20 per cent neon. This mixture is used in the mercury sign lamps as the carrier gas, and is necessary for its operation through the wide range of temperatures to which they are subjected. The blue of the argon blends with the blue of the mercury to give the characteristic color.

The colors obtained with clear glass tubes are red (neon), pinkish white (helium) and blue (mercury-argon-neon). Other colors can be obtained by using colored glasses, many varieties of which are available. These in combination with the gas-discharge colors may provide a great variety of shades.

Yellow glass known as "noviol" may be used with mercury-argon gas to produce the popular green. Noviol glass may be used with helium gas to produce the yellow "gold" tube.[1]

The neon lamps just described are of the cold-cathode type.

The *hot-cathode* neon lamp having a preheated filament with a barium oxide coating offers a more efficient unit. It operates with a relatively high intrinsic brilliancy. Because of its greater color contrast with surrounding lamps it has proven to be an excellent unit for signal purposes and for markers for docks, ferry slips in harbors, obstruction lights, and for aviation-signal purposes. Also since the wave length of the light is longer than white light it will not be absorbed and scattered in fog and heavy weather to the same extent that would occur in the case of shorter light waves.

MERCURY AND SODIUM LAMPS

Mercury and sodium vapors form the bases of the most efficient commercial light sources at the present time.

Mercury-vapor light is always of a bluish green. It is very deficient in red rays and to lesser amounts in certain other colors. The color can be improved by operating the vapor under higher pressure, but the color characteristics remain.

The sodium-vapor light consists almost entirely of an orange-yellow band. Both the mercury-vapor and sodium-vapor lights distort color values and are obviously unsuitable for many purposes.

There are two methods of modifying the color of the light from vapor sources. Different materials may be combined in a single arc and two lamps of different types can be enclosed in the same luminaire. Neither of these methods has so far produced suitable approximations of daylight color with the sodium lamp. When two materials are mixed in a single tube one of them tends to predominate at the expense of the other. This tendency is strong in combinations where sodium is one of the elements. As to the second method, no practical light source is known which has the proper color characteristics for combination with sodium.

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[1] For further information on neon lamps the reader is referred to S. C. Miller and D. G. Fink, *Neon Signs*, McGraw-Hill Book Company, 1935.

The high-intensity mercury light is more satisfactory in both respects. Combinations of cadmium and zinc with the mercury may produce a light that, while somewhat deficient in red, gives ordinary objects a fairly natural appearance. This involves a lowering of the efficiency.

Mercury-vapor and incandescent lamps can be combined in the same luminaire to give a synthetic white light. This light is obviously not suitable for color matching because of its abnormal spectral distribution. However, the high efficiency and the cool white color, mixing well with daylight, make it a desirable light for office, school, factory lighting and similar applications.

The combination with incandescent lamps overcomes the objection that may arise due to the slow starting of the mercury-vapor lamps.

Cooper-Hewitt Mercury-vapor Lamp.—This lamp was developed by Peter Cooper Hewitt who produced in 1901 an arc in vacuum in a 1-in. glass tube, 45 in. long, for 110-volt direct-current circuits. The tube was suspended at an angle of about 15 deg. with the horizontal. The lower end contained a small amount of mercury. The terminals were at opposite ends of the tube, and the arc was first started by tilting the tube by hand, so that a thin stream of mercury bridged the space between the electrodes. The current immediately vaporized the mercury, establishing the arc. A resistance was placed in series with the arc to maintain a constant current from a constant-potential circuit. Automatic starting devices were later applied, one of which consisted of an electromagnet that tilted the lamp and another consisting of an induction coil which on discharging produced a high voltage which started ionization at the surface of the mercury and started the arc. The lamp consumed 3.5 amp. at 110 volts and gave 12.5 lumens per watt with direct current.

The alternating-current lamp operates on the principle of the mercury-arc rectifier. Current can pass through the tube in the direction of the mercury cathode only. To use both halves of the alternating-current wave necessitates two anodes. The mercury cathode is connected through an inductance to the mid-point of a transformer, while the two anodes at the other end of the tube are connected to the outer terminals of the transformer, as shown in Fig. 4-1. Once the lamp is started the two halves of the transformer operate alternately, the current shifting from one anode to the other with each alternation, but continuing as a pulsating direct current through the lamp and the mercury cathode to the mid-point of the transformer. The inductance in series with the negative electrode maintains the current during the time of zero voltage and tends to smooth out the pulsations in the rectified current. A study of the oscillograms shown in Fig. 4-2 will show the voltage and current relations in the lamp. The 110-volt lamp operates at about

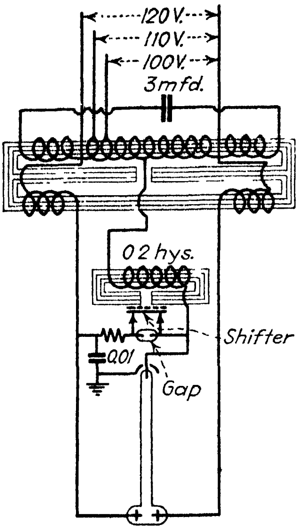

FIG. 4-1.—Diagram of connections for the Cooper-Hewitt mercury-vapor lamp.

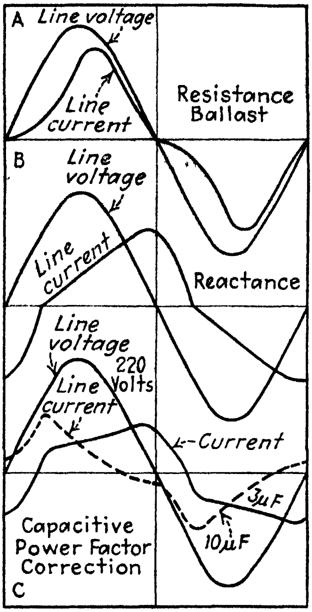

FIG. 4-2.—Effect of reactance ballast and a multiple capacitor on power factor.

450 watts, 3.7 amp. in the tube and at a power factor of about 85 per cent. The efficiency is about 15 lumens per watt. The lagging component of the supply current can be reduced by the use of a multiple condenser. An extended winding on the primary of the transformer (Fig. 4-1) provides some 540 volts for a 3-mfd. condenser.

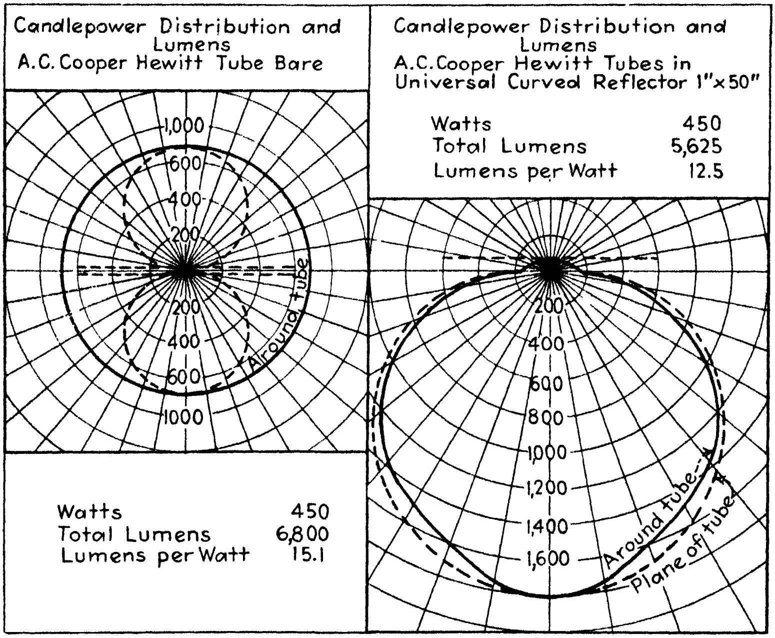

FIG. 4-3.—Distribution curves of bare and reflector-equipped low-pressure mercury arc.

The candle-power curves for the bare lamp and for the lamp equipped with a reflector are shown in Fig. 4-3.

High-intensity Mercury- and Sodium-vapor Lamps.[1]—The new high-intensity mercury- and sodium-vapor lamps differ from the Cooper-Hewitt lamps in their compactness and increased brightness and in the nature and quantity of their radiation.

Instead of the gravity-controlled pool of mercury of the Cooper-Hewitt lamp the new lamps have oxide-coated cathodes.

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[1] L. J. BUTTOLPH, "High-Intensity Mercury and Sodium Arc Lamps," *J. Soc. Motion Picture Eng.*, vol. 24, p. 110, 1935.

These electrodes may consist of a coiled tungsten wire with a fused coating of an alkaline earth, notably barium oxide, and when raised to a temperature of about 900°C. produce a low-voltage cathode suitable for gas- and vapor-conduction devices, *e.g.*, mercury, sodium, and neon lamps, the functioning of the cathodes being largely independent of the nature of the surrounding gas. The one requirement for the proper operation of this type of cathode is the definite temperature already specified.

Oxide-coated cathodes may be divided into two classes, depending upon whether their heating is solely that produced by the arc current and the voltage drop at the electrodes or whether additional heating energy is supplied to the cathode from an auxiliary device. The arc-heated type of cathode happens to be used in the high-intensity mercury arc, whereas the separately heated type is used in current models of the sodium arc. The use of either type of oxide-coated cathode at once removes restrictions as to operating position, and so permits the same flexibility of use possible with incandescent lamps.

The light-source length, or distance between the electrodes, of the new lamps is one-sixth to one-eighth that of standard Cooper-Hewitt lamps, a fact that profoundly influences both their operating characteristics and their practical utilization. Electrically the result is instantaneous starting when cold, without any such electrical or mechanical starting means as have usually characterized low-voltage arcs. The compactness results also in such a relatively high normal operating temperature and vapor pressure that the mercury arc does not restart until it has cooled for an interval, which can be shortened by using one of the arc-starting devices long in use with gas-conduction lamps.

Although both the sodium and mercury arcs can be operated on direct current, the fact that the more efficient types are, respectively, lower and higher in operating voltage than the conventional direct-current sources has led to a standardization at present on alternating-current models. It is also proper to point out the additional practical advantages of alternating-current operation inherent in the voltage adjustment possible with transformers, the efficiency of reactive rather than resistive ballasting, and the combination of those two factors with safety in the insulating line transformer with high-leakage reactance.

In this connection, it should be noted that all arcs are inherently constant-current devices, and that arc-ballasting auxiliary devices are necessary only because constant-voltage rather than constant-current electrical distribution happens to be the practice. Series operation on constant-current lines is common in highway lighting practice and is being used with these new gas-conduction arcs.

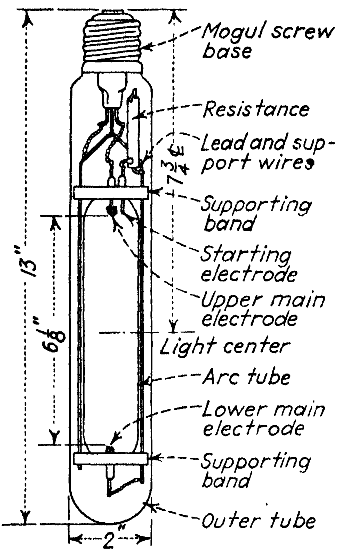

FIG. 4-4.—The high-intensity mercury-vapor lamp.

When operated on a more or less constant-voltage line with reactive ballasting the lamps have a power factor of about 0.65, which may be corrected by condensers, in the usual manner, to over 0.90, this residual apparent power factor being due to a distortion rather than a time displacement of the current wave.

The stability and regulation characteristics of gas-conduction lamps can be made anything within reason, as they are fixed arbitrarily by the amount of ballasting used. Stability, persistence of the arc upon sudden decreases in line voltage, and regulation, changes in arc current or light, with changes in supply voltage, can be improved by increasing the ratio of the ballast voltage to the arc voltage drop, *i.e.*, by absorbing relatively more of the available voltage and energy in the ballast unit, with the obvious result of decreasing the over-all efficiency. A similar design compromise is involved in the lumen per watt rating of a given gas-conduction lamp. The efficiency may be increased by taking a shorter operating life, or a longer life may be had by operating at a lower efficiency.

High-intensity Mercury-vapor Lamp.[1]—The details of construction of this lamp are shown in Fig. 4-4. Electrodes of barium strontium oxide fused to coiled tungsten wire are located at opposite ends of a glass tube. Near the upper end of the tube is a starting electrode that is electrically connected through a resistance to the lower electrode. When a voltage is applied to the lamp an electrical potential exists between the starting and upper main electrodes causing an electrical emission from the active material of the main electrode, thus starting the tube arc.

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[1] *Trans. Illum. Eng. Soc.*, vol. 31, p. 583, 1936.

The arc tube contains a small amount of mercury, which is very carefully measured so as to maintain accurately the desirable vapor pressure, which in this lamp is about normal atmospheric pressure. The arc tube also contains a small amount of pure argon gas, which acts as a conducting medium to assist in starting the arc and before the mercury is vaporized.

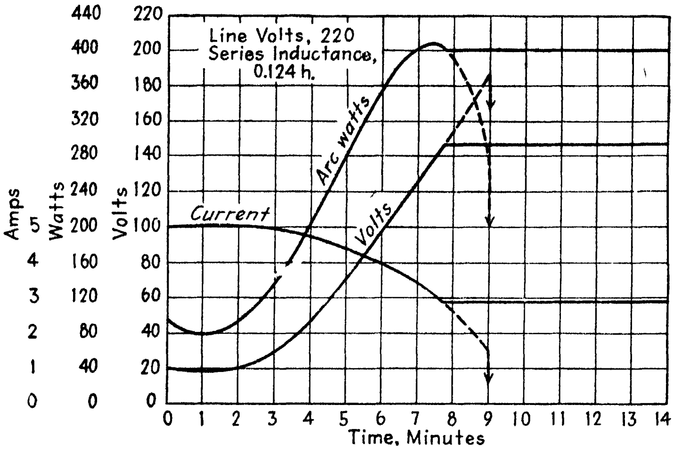

FIG. 4-5.—Electrical characteristics of 400-watt arc between time of starting and complete vaporization of mercury.

The high-intensity mercury lamp is made in three sizes of 400, 250 and 85 watts. The 400-*watt lamp,* illustrated in Fig. 4-4, consists of a discharge tube mounted within a sealed glass tube of larger diameter, known as the jacket, which makes the lamp less subject to the effect of the surrounding temperature. The lamp operates on 220 volts with a series reactor, or at any voltage with a reactive transformer. The power factors of the 400-watt lamp with series reactor and with high-reactance transformer ballast are 65 and 70 per cent, respectively, which can be raised to 94 per cent by connecting a suitable capacitance across the lamp. The lamp produces about 35 lumens per watt over-all with ballast accessory. The average life is 2,000 hr.

When the lamp is turned on the tube takes about 20 volts and 5 amp. The argon arc is seen for about 2 min. as a bluish glow which fills the entire arc tube. After a few minutes the mercury becomes vaporized and the tube operates at 150 volts and 2.9 amp. The performance of this lamp is shown in Fig. 4-5.

The arc appears as a brilliant pencil of light at the center of the cylindrical tube. This is in contrast to the sodium and low-pressure mercury lamp, where the glow seems to fill the entire diameter. It is necessary to operate the lamp in a vertical position to prevent injury to the glass from the heat of the arc. As now made, the lamp is less efficient if operated base down. When heated the vapor pressure within the inner tube is sufficient to prevent an immediate restarting of the lamp if for any reason it should be extinguished. Five minutes or more for cooling is necessary, after which the lamp will start automatically if the electricity remains switched on.

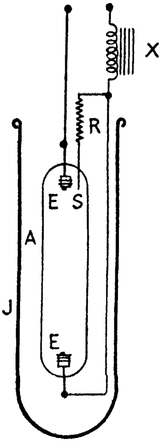

FIG. 4-6.—Circuit diagram of lamp and series reactor.

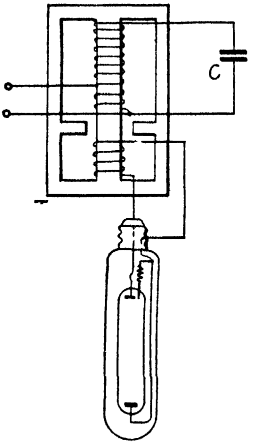

FIG. 4-7.—Circuit diagram of lamp and high-reactance transformer.

The 250-*watt lamp* consists of an arc tube only. It is designed for burning in any position. Its uncorrected power factor is about 50 per cent, which is raised to 92 per cent by capacitance. Its over-all efficiency with necessary ballast auxiliary is 25 lumens per watt. The lamp is 8 in. over all and 1⅛ in. in diameter. Its average life is 2,000 hr.

The circuit diagrams for the high-pressure lamp are shown in Figs. 4-6 and 4-7. The reactor in Fig. 4-6 has an air gap to prevent saturation of the iron. It limits the current during starting and stabilizes the arc and minimizes the flicker in the light produced. The high-reactance transformer of Fig. 4-7 transforms from line voltage to tube voltage, may be designed with the required reactance, and provides for the use of a condenser to raise the power factor.

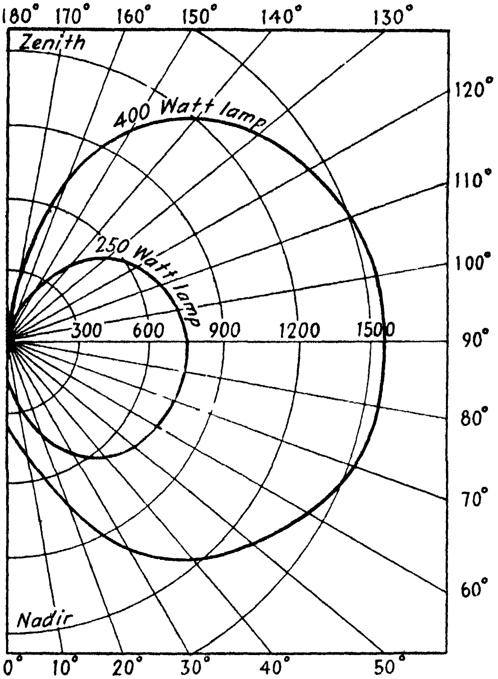

FIG. 4-8.—Candle-power distribution curve of bare 400-watt lamp, and bare 250-watt lamp.

The candle-power distribution curves of the bare 400-watt and of the bare 250-watt lamps are shown in Fig. 4-8.

These lamps can be supplied with any of the ordinary designs of luminaires. Special designs are necessary for concentrated beams because of the length of the luminous section. The intensities with the cylindrical parabolic and the right conical reflectors are shown in Fig. 4-9.

The light output from alternating-current arc discharges follow rather closely the instantaneous values of the arc current, as will be seen from Fig. 4-10. There also are plotted the cyclic variation in arc voltage, current, and light intensity for a 400-watt lamp. The power factor of the arc is 0.94 and is due to the nonsinusoidal wave forms.

A new type of high-pressure mercury-vapor lamp[1] known as the capillary lamp has a quartz tube of $\frac{5}{64}$-in. internal diameter and about $\frac{1}{4}$-in. external diameter. In principle, the length may be of any predetermined value, according to the amount of light required. The

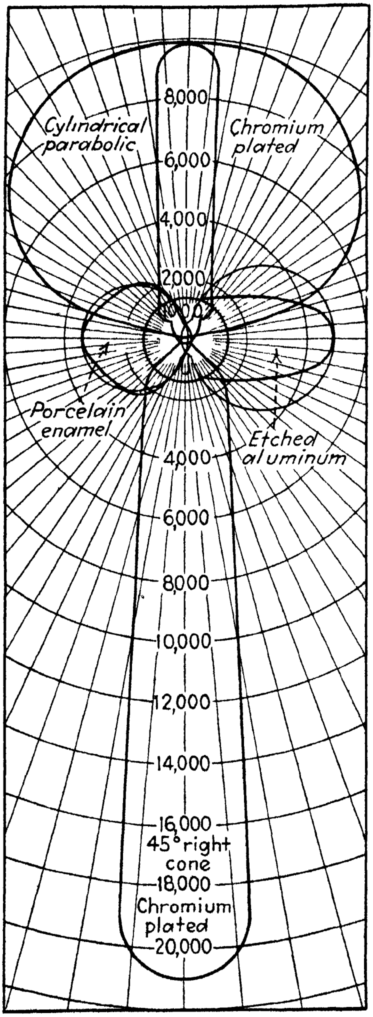

FIG. 4-9.—Comparison of various types of reflectors used with a 425-watt, high-intensity mercury arc.

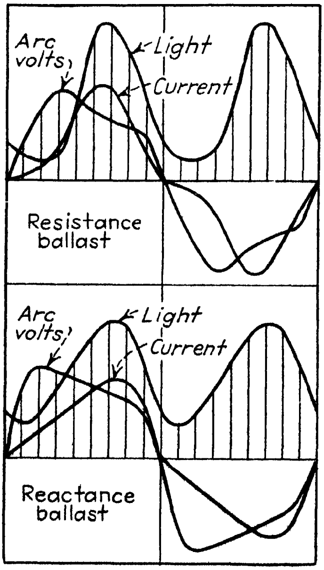

FIG. 4-10.—Effect of the ballasting method on arc current and light.

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[1] *Electrician*, vol. 115, p. 439, 1935.

tube has a tungsten electrode at each end, sealed into the quartz, with an interposed layer of a special grade of glass. This latter is due to the difference in thermal expansion of tungsten and quartz.

The electrode tips are coated with a deposit of an alkaline earth to facilitate the emission of electrons necessary for the electrical discharge. These tips, moreover, each just project from a small drop of mercury which condenses at each end. This small lamp is then placed inside a jacket containing running water.

In common with all other electric-discharge lamps, it requires a stabilizing device to ensure steady operation. This is achieved by feeding the lamp via an autotransformer, the self-induction of which stabilizes the discharge, while the "no-load" voltage generated suffices to "strike" the lamp. Up to the present time a gradient not exceeding 1,250 volts per inch has been accepted as satisfactory in all normal applications. Under these conditions the lamp consumes about 1,500 watts per inch, the current being approximately 1.35 amp. The power factor of the lamp itself is about 0.9.

A spectroscope reveals the fact that the radiation shows a continuous spectrum upon which the mercury lines stand out, being greatly broadened. The continuous background extends throughout the entire visible spectrum, including the red rays. As the result of this the light from this new lamp causes practically no color distortion, as opposed to other electric-discharge lamps at present in use.

Preliminary measurements have furnished the following data regarding the energy distribution over the spectrum. At 8 in. from a 500-watt lamp the energy received per square inch between 0.5 and 0.6μ (the middle of the visible spectrum) is equal to that of direct sunlight, between 0.3 and 0.4μ (ultraviolet) this energy is equivalent to five times that of sunlight, whereas between 0.6 and 1.0μ (chiefly infrared) it attains only half as much. Owing to the presence of the glass tube containing the cooling water, however, the ultraviolet radiation is totally absorbed.

The luminous efficiency is from 50 to 60 lumens per watt. On the other hand, the light source itself is of very small size, the diameter of the luminous part being less than $\frac{3}{64}$ in. This results in a very high brightness, which may attain as much as

260,000 candles per square inch, about one-quarter of the brightness of the sun as it appears to a terrestrial observer. The brightness of the ordinary carbon arc is about 110,000 candle power per square inch. The small size and high brightness of this lamp promise to make it of great value where it is necessary to project light in the form of a concentrated beam, *e.g.*, in cinema projectors, lighthouse beacons, etc. This lamp has been developed commercially in this country in the following unit.

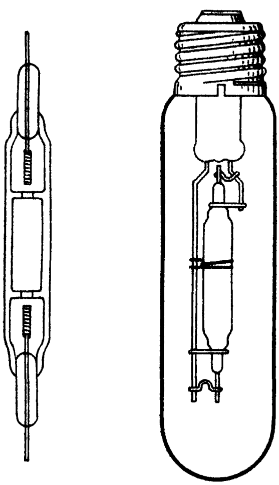

FIG. 4-11.—The quartz arc and complete 85-watt mercury lamp.

The 85-*watt mercury lamp*,[1] has an output of 3,000 lumens and an initial efficiency—lamp alone—of 35 lumens per watt. It consists of a very small light chamber of quartz enclosed in a $1\frac{1}{4}$-in. tubular bulb $5\frac{5}{8}$ in. long. About 18 watts is consumed in the required accessory, which provides the 450 volts for starting and acts as ballast. The voltage at the arc terminals is 250 volts at a normal current of 0.4 amp. A low pressure of argon gas provides the glow discharge necessary for the initial heating of the oxide-coated electrodes.

The life of the lamp under the above conditions is about 500 hr. The construction of the light chamber and its size in proportion to the lamp are shown in Fig. 4-11.

Sodium-vapor Lamp.—This lamp, like the high-pressure mercury-vapor lamp, consists of a hermetically sealed glass tube. At each end is an electrode which may be made up of an elliptical foil of molybdenum and a coiled tungsten-filament barium oxide coated. During one-half cycle, one of the oxide-coated filaments acts as the cathode, while the molybdenum foil at the opposite end acts as the anode. For the other half cycle the other oxide-coated filament becomes the cathode and the other molybdenum terminal becomes the anode.

The bulb contains a small amount of pure metallic sodium and neon gas at a low pressure to assist in starting. The cathodes are preheated by a current applied at low voltage to the filaments or the heaters may be in series with the electrodes for the series circuit lamps (Fig. 4-12). After a preheating period the lamp glows with the characteristic red neon color. As the temperature rises the discharge gradually acquires the orange-yellow of the sodium-vapor arc. The maximum output is reached in about 30 min. but acceptable lighting conditions are usually obtained in 10 or 15 min. Since the lamp will not cool completely during short power interruptions the time of recovery from such an interruption is usually short.

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[1] *Trans. Illum. Eng. Soc.*, vol. 31, pp. 451, 583, 1936.
J. Soc. Motion Picture Eng., vol. 28, p. 43, 1937.

The sodium-vapor lamp for alternating-current circuits is available commercially in two sizes.

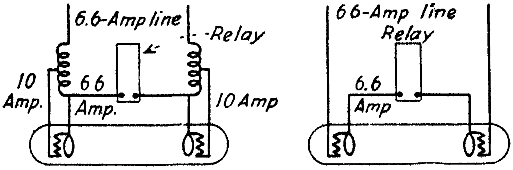

FIG. 4-12.—Series constant-current sodium-lamp circuits with multiple (left) and series (right) electrode heaters.

A 10,000-*lumen lamp* rated at 200 watts in the arc and using about 25 watts in the auxiliary has an over-all efficiency rating of 45 lumens per watt when reactive-ballasted for 30 per cent of the total voltage and rated for a useful life of 1,350 hr. Its over-all power factor is about 65 per cent, which may be corrected to 90 per cent by means of a condenser. The light source itself is 9 in. long, 3 in. in diameter, and has an average brightness of 37 candles per square inch.

A 6,000-*lumen lamp* rated at 150 watts in the arc and using about 15 watts in the auxiliary has an over-all efficiency rating of 36 lumens per watt when reactive-ballasted for 30 per cent of the total voltage and rated for a useful life of 1,350 hr. The light source itself is 7 in. long, 2.5 in. in diameter and has an average brightness of 34 candles per square inch.

Both these sodium lamps must be enclosed in vacuum jackets (Fig. 4-13) to ensure the temperature and sodium-vapor pressure necessary for efficient operation. For the same reason an initial interval of about 20 min. is required to attain an efficient operating temperature.

The reaction between soda vapor and ordinary glass necessitates a special glass for the tubes of the sodium-vapor lamp. Glass high in boric-acid content has been found surprisingly sodium resistant, but difficult to manufacture. The present solution[1] of the problem has been the use of a glaze of high boric-acid content fused onto the inner surface of the arc tube to form what may be called a cased glass. This is the method used in all domestic and most of the foreign sodium lamps, and it is proving very effective.

Although a smaller percentage of the total energy put into sodium lamps emerges as visible radiation, the pair of lines are fortunately so placed relatively to the visibility curve, that the luminosity is more than three times that of incandescent light, and hence their efficiency is two to two and one-half times that of a 20 lumen per watt incandescent lamp.

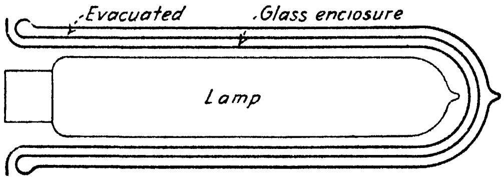

FIG 4-13.—Thermal insulation of the sodium lamp.

This efficiency makes the lamp attractive for applications in which color values are of little importance, *e.g.*, highway, flood, beacon, and spectacular lighting.

In Table 4-1 are given the general characteristics of various gas and vapor lamps representing their performance in the year 1935.

Spectra of Gas and Vapor Lamps.—The spectra of gas and vapor lamps consist of lines or bands characteristic, in wave length and energy content, of the specific gas or vapor instead of an infinite number of lines, or a single band, characteristic in energy content and distribution, only of the temperature of the source.

The spectra of some of the various luminescent gases and vapors obtained by a prism spectrometer are shown in Figs. 4-14 and 4-15.[2] These spectra are qualitative only and give no indication

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[1] L. J. BUTTOLPH, *Trans. Electrochem. Soc.*, vol. 65, p. 205, 1934.

[2] L. J. BUTTOLPH, *Trans. Illum. Eng. Soc.*, vol. 30, p. 147, 1935.

TABLE 4-1.—GENERAL CHARACTERISTICS OF VARIOUS GAS-CONDUCTION LAMPS*

Sources†	Method of operation	Power factor	Watts in aux.	Watts in arc	Tube diameter, in.	Arc amp.	Arc length, in.	Arc voltage	Watts per linear in.	Lumens per linear in.	Candles per sq. in.	Over-all lumens per watt
H.-v. neon	Reactance transformer	55	4	36	0.45	0.03	100	2,050	0.24	5.8	1.30	14.5
H.-v. neon	Reactance transformer	55	5	50	0.60	0.05	100	2,000	0.30	7.2	1.20	13.0
H.-v. mercury	Reactance transformer	55	5	45	0.45	0.03	100	2,300	0.20	1.6	0.36	3.2
H.-v. mercury	Reactance transformer	55	10	85	0.60	0.05	100	2,100	0.55	1.9	0.32	2.0
L.-v. l.-p. mercury	110-volt d. c.	..	135	250	1.00	3.5	50	71	4.1	120.0	12.2	16.0
L.-v. l.-p. mercury	A.-c. rect. resistive ballast	90	175	275	1.00	3.7	50	74	4.6	135.0	13.6	15.0
L.-v. l.-p. mercury	A.-c. rect. resistive ballast	90	100	150	1.00	3.7	22	40	4.6	135.0	13.6	12.0
L.-v. l.-p. mercury	A.-c. rect. resistive ballast	90	125	175	0.75	2.5	35	70	4.2	115.0	15.4	13.5
L.-v. h.-c. neon	A.-c. rect. resistive ballast	90	200	300	1.00	3.5	18	70	11.7	275.0	27.8	10.0
H.-p. quartz mercury	Uviarc d. c.	..	250	650	0.70	4.0	6	160	100.0	3600.0	520.0	24.0
High-intensity mercury	Full-wave a.-c. ind. ballast	65	25	400	1.30	2.9	6	160	63.0	2250.0	175.0	32.0
Sodium—10,000‡	Full-wave a.-c. ind. ballast	65	25	200	3.00	6.6	9	25	15.5	1100.0	27.0	45.0
Sodium—6,000‡	Full-wave a.-c. ind. ballast	65	15	150	2.50	5.0	7	20	14.3	850.0	34.5	36.0

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* L. J. BUTTOLPH, *Trans. Illum. Eng. Soc.*, vol. 30, p. 147, 1935.

† H.-v., l.-v., h.-p., l.-p., and h.-c. indicate high and low voltage, high and low pressure and hot cathode.

‡ Tentative data based on a depreciation of about 15 per cent, for each successive 1,000-hr. interval of operation, from a rated rather than actual initial output. Intrinsic brilliancy based on total emitting surface area of tube or bulb.

of the relative luminous efficiencies of the various gases and vapors—merely the effects on a photographic plate. Thus a weak line in the blue may show as intense as a stronger, red line.

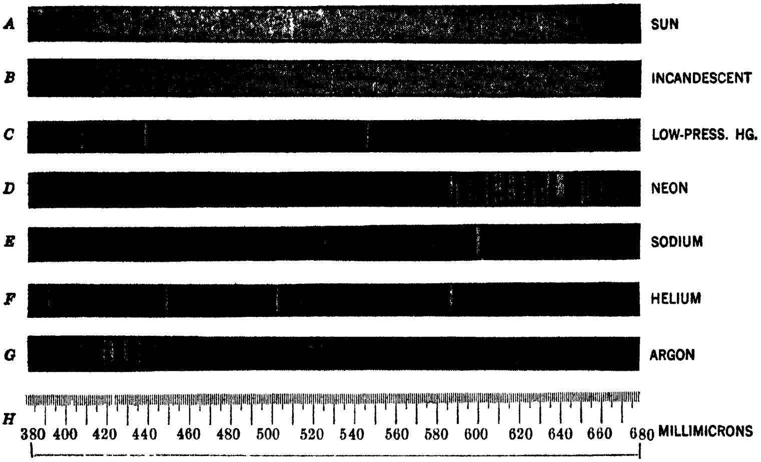

Fig. 4-14.—Normal spectra of various gaseous-conduction lamps.

In further study of these spectra it should be borne in mind that the sensitivity of the eye is at a maximum for a wave length about 0.556μ.

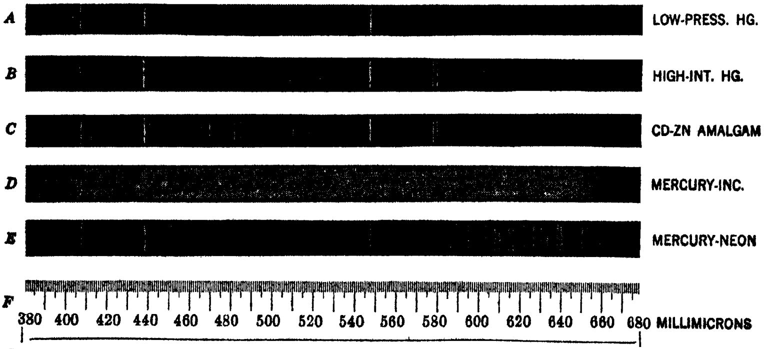

Fig. 4-15.—Spectrograms of gaseous-conduction light containing augmented spectra.

The combination of two or more vapors or gases and the combination of vapor or gas lamps with incandescent lamps offer many possibilities. By a study of the spectral distributions for the various suitable substances as given in the figures, one may make a preliminary guess of the possibilities of certain combinations for specific results. Some of these combinations are shown in the spectrograms of Fig. 4-15*C*. The addition of cadmium and zinc to the high-intensity arc made color discrimination throughout the whole spectrum somewhat better. The combined spectra of the mercury arc and the incandescent lamp may be seen in Fig. 4-15*D*, and Fig. 4-15*E* shows the combined spectra of the neon tube and the mercury lamp side by side or in the same luminaire.

Since gas and vapor light sources only have line spectra with no width or continuity as in the case of incandescent-light spectrum, their luminosity can only be compared graphically with that of the sun or incandescent light arbitrarily assigning to them a uniform width symmetrically placed relative to their wave length. Thus in Fig. 4-16*D* the actual relative intensities are proportional to the areas of the respective mercury lines while the widths are such that the ruled portions are proportional to the products of the intensities by their visibilities, *i.e.*, proportional to their luminosities.

The ruled areas or luminosities of each kind of light represented in Fig. 4-16 are made equal to each other so the total areas represent graphically the theoretically visible energy. The ratio, in each case, of the luminosity area to the total-energy area will then be a visual utilization factor characteristic of the light distribution and unrelated to the source. It is to be noted that in the case of the low-pressure mercury arc, over half of the theoretically visible light is of so short a wave length as to be but 1 to 2 per cent visible. The high-pressure mercury arc gets all its added efficiency by an increase in the relative intensity of the 577–579 lines. The sodium lines, because of their favorable location relative to the visibility curve, show a high utilization factor and produce a given luminosity with but a fraction of the energy required in the incandescent lamp.

The percentage of the total energy put into light sources or, in the case of the sun, emitted from it, which is radiated as theoretically visible, can be determined by well-known methods (Table 4-2, Cols. *b*, *c*). Less than 15 per cent of the energy put into these lamps is converted into theoretically visible light. If all this energy were concentrated at the wave length to which

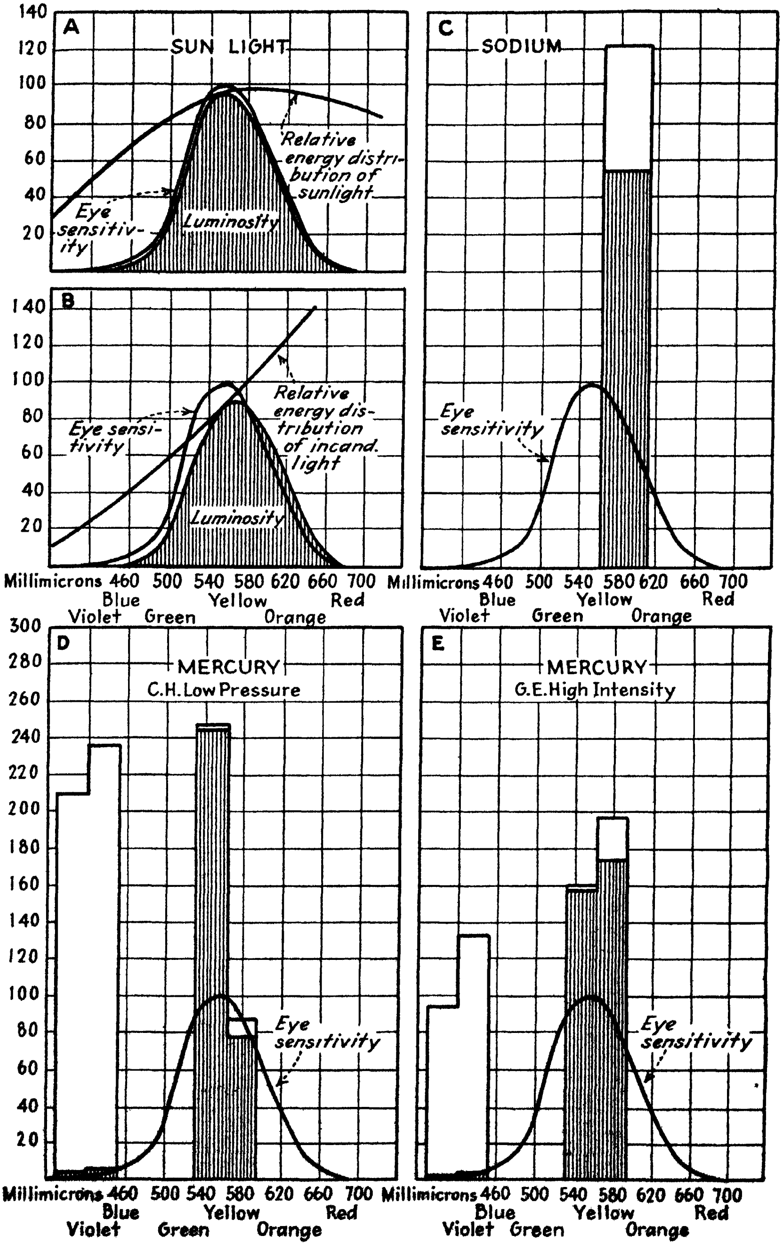

FIG. 4-16.—Graphic indication of energy required to produce comparable luminosities by light of various energy distributions.

the eye is most sensitive—about 556 millimicrons—its utilization might be rated as 100 per cent (Col. *d*) in comparison with the lower utilization factors determined graphically as suggested by Fig. 4-16 for sun and artificial light. The products of the percentage of visible radiation and the utilization factor give an over-all visual utilization factor (Col. *e*) which is sometimes called the reduced luminous efficiency since it is also the ratio of the practical lumens per watt rating of a source to the theoretical maximum of 620 lumens per watt possible with a monochromatic source of wave length 556 (Col. *f*).

Table 4-2, Col. *e*, shows directly in percentage the efficiency of the sources in comparison with a theoretical monochromatic source. A more practical comparison is with a fictitious white-light source emitting no energy outside the visible regions. Column *g* shows directly in percentage the efficiency of the sources in comparison with such a fictitious white-light source.

TABLE 4-2.—RELATIVE ENERGY, UTILIZATION, AND EFFICIENCY OF LIGHT*

(*a*) Source	(*b*) Per cent invisible	(*c*) Per cent visible	(*d*) Visual utilization	(*e*) Reduced lum. eff.	(*f*) Lumens per watt	(*g*) Relative white efficiency
White light 380–700 only	0.0	100.0	35	35.0	220	100.0
Monochrome 556 only	0.0	100.0	100	100.0	620	280.0
Sunlight	60.0	40.0	40	16.0	100	45.0
Incandescent lamp (500 watts)	86.0	14.0	23	3.2	20	9.0
Neon (ind. ballast, 400 watts)	92.0	8.0	32	2.6	16	7.25
Hg. (high-intensity inductive ballast, 400 watts)	91.0	9.0	58	5.2	32	14.5
Hg. (C.H. low-pressure resistive ballast, 450 watts)	94.6	5.4	43	2.3	15	6.75
Sodium arc (inductive ballast, 225 watts)	89.0	11.0	76	7.3	45	20.0
Helium (ind. ballast, 500 watts)	98.9	1.1	58	0.65	4	1.8

* BUTTOLPH, *Trans. Illum. Eng. Soc.*, vol. 30, p. 160, 1935.

Ultraviolet Radiation and Fluorescence.—The use and application of ultraviolet radiation and fluorescent materials in the production of luminous surfaces, spectacular effects, decorative lighting, and light sources of higher efficiency offer much promise for the future.

Carbon arcs with metallic oxides in cored carbons have been given a selective radiation which, in combination with their characteristic cyanogen band, has made possible their use as the only available means of projecting ultraviolet in useful intensities a distance of more than a few feet.

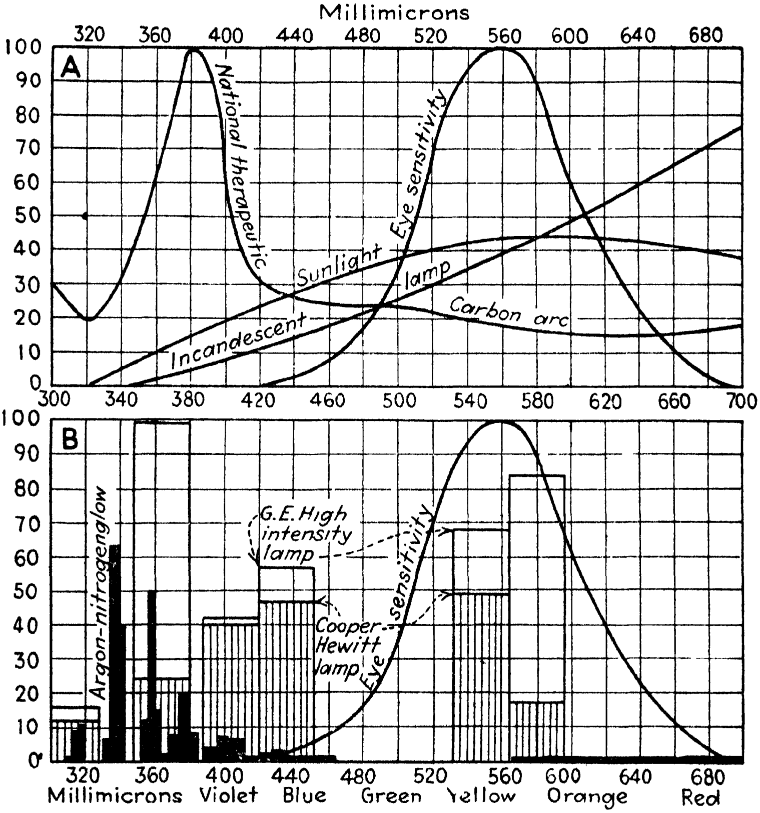

FIG. 4-17.—Relative energy distribution of continuous- and line-spectra sources used to produce fluorescence.

Gas and vapor lamps, because of the selective nature of their radiation, offer inherent possibilities as ultraviolet sources and in this respect the mercury arc is unique. The mercury arc has the further fortunate characteristic that as the intrinsic brilliancy is increased, *e.g.*, in the high-pressure quartz-mercury arc, the relative energy content of the 366 line increases even more than that of the yellow and green lines. The energy radiations from the source of ultraviolet mentioned above are shown in Fig. 4-17.[1]

Since these sources are too large for projector work, they are used for such cases as securing of high-intensity ultraviolet free from visible blue through such filters as No. 587 of Fig. 4-18. Low-pressure mercury arcs, on the other hand, have the advantage because of their low operating temperature that the arc tubes may be made of filter glass and the tube may be used with suitable reflectors to secure good distribution of ultraviolet.

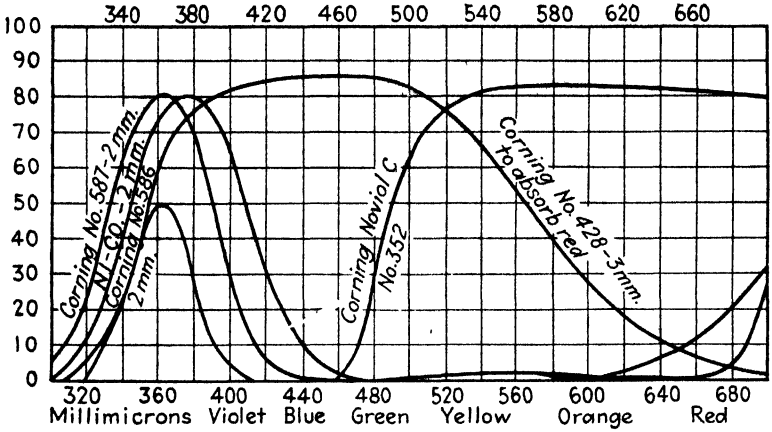

FIG. 4-18.—Transmission curves of filters used to isolate ultraviolet radiation.

These filters are available as plates and tubes and even in a heat-resisting glass for use in the beams of carbon spot lamps. The transmission curves of some of the filters used to isolate ultraviolet radiation are shown in Fig. 4-18.[1]

Fluorescent Glass.—Recently so-called fluorescent glasses have been manufactured here and abroad in an attempt to alter the color of mercury sign tubing and mercury light sources, and to add to their luminous efficiency through the conversion of invisible ultraviolet radiation inside to visible radiation outside the tube.

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[1] *Trans. Illum. Eng. Soc.*, vol. 31, p. 21, 1936.

Partially fluorescent lamps have recently been developed using these materials as a coating or glaze on the inner surfaces of the bulb or tubes as is done with the cathode-ray tubes. For the same purpose an interesting line of so-called fluorescent glasses has recently become available for the fabrication of lamps in which the arc tube itself contributes a continuous or banded spectrum to the normal line spectrum of the gas or vapor used.

Two results were anticipated by the manufacturers of such tubing—a change from the monotony of red, blue, and green luminous signs—and new artificial sources of light, which in their effect might be compared with daylight.

It is claimed that by the addition of heavy metals (especially cadmium) to zinc silicates and zinc sulphides the color of the luminescence may be changed from greenish-white to lemon yellow and strawberry red. Luminescent tubing made from such glasses is claimed to give efficiencies up to 370 per cent of that of a clear glass tube under certain specific conditions.

Luminescent Powders.—Research shows that the use of luminescent powders in tubular vapor lamps may greatly enhance the brilliancy. When the radiation from mercury vapor impinges on suitable luminescent material it is degraded into longer wave lengths (fluorescence) in the visible part of the spectrum. The common materials are zinc and cadmium, but there are many others. They are usually coated on the inside surface of the tube. Patterson[1] mentions a mercury "sign-type" tube which, without powder, gave about 250 lumens at 5 lumens per watt. With its inside surface coated with one of the new powders its light was raised to 3,000 lumens at 60 lumens per watt without any increase in electrical energy.

An attractive feature of luminescent powders is that they change the nature of the spectrum from the line spectrum characteristic of the vapor lamp to the band type of spectrum. In this respect they are conveniently useful for filling in gaps in the line spectra of the vapors and gases.

In Fig. 4-19 are shown the spectral distributions of luminescent powders stimulated by mercury, compared with the spectral distribution of mercury vapor itself.

Brightness of Light Sources.—The intensities of some of the common sources of light in candle power per square centimeter

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[1] *Electrician*, vol. 116, p. 127, 1936.

TABLE 4-3.—BRIGHTNESS OF LIGHT SOURCES

Source	Candle power per square centimeter	Color temperature degrees Kelvin
Cold-cathode neon-mercury tube (blue)	0.016	
Cold-cathode neon-mercury tube (green)	0.025	
Cold-cathode neon-mercury tube (red)	0.078	
Moore tube	0.093	
Dark, overcast sky	0.16	
Cloudy sky (dark)	0.22	
Moon (selective reflection)	0.25	4125
Blue sky	0.4	
Overcast sky	0.5	
Candle flame	0.54	1930
Kerosene flame	1.3	2055
Cumulus sky	1.6	
Tungsten lamp (inside-frosted bulb, 25 watts and larger)	2.2 to 4.6	
Mercury-vapor lamp (glass tube)	3.4	
Welsbach gas mantle	3.1 to 5.4	
Hot-cathode neon tube (red)	5.4	
Acetylene flame	6.7	2400
Tantalum filament, 4.9 lumens per watt	53	2260
Carbon filament, 3.2 lumens per watt	71	2165
Gem filament, 4.0 lumens per watt	78	2200
Mercury arc (quartz tube)	93 to 155	
Tungsten filament (10 lumens per watt vacuum lamp)	206	2504
Nernst glower (2.3 watts per candle)	258	2400
Tungsten filament (10 lumens per watt gas-filled lamp)	469	2670
Tungsten filament (1,000-watt stereopticon lamp)	2,065	3175
Tungsten filament (900-watt movie lamp)	2,660	3220
Tungsten filament (10-kw. lamp)	3,050	3300
Tungsten filament (30-kw. lamp)	3,050	3300
Tungsten filament (20 lumens per watt gas-filled lamp)	1,225	2980
Sun, when near the horizon	600	
Sun, 30 deg. above the horizon	77,500	
Sun, at earth's surface (calculated)	165,000	5600
Sun, outside earth's atmosphere (calculated)	224,000	6500
Carbon arc crater	14,250	
Mercury arc ($\frac{5}{64}$-in. quartz tube)	40,000	
Magnetite arc	620	
Flaming arc	775	
Black body at 5000°K.	84,000	5000

are given in Table 4-3, composed of data compiled from various sources, chiefly from results by Millar and Gray,[1] and Forsythe.[2]

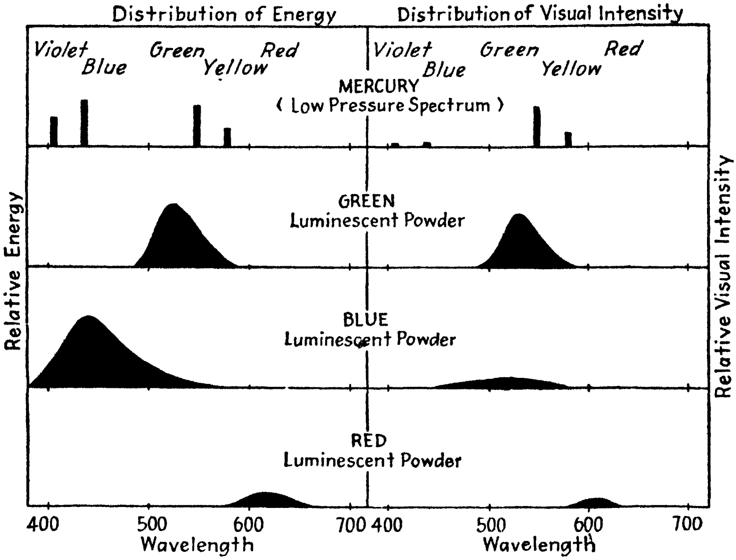

FIG. 4-19.—Spectral distribution and luminosity of radiation from luminescent powder stimulated by mercury vapor.

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[1] *Standard Handbook for Electrical Engineers*, 6th ed., p. 1648, 1933.

[2] *Gen. Elec. Rev.*, vol. 26, p. 830, 1923.

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CHAPTER V

PRINCIPLES OF PHOTOMETRY AND TYPES OF PHOTOMETERS

In measuring the luminous intensity of a source of light the standard of candle power is the fundamental feature and its reliability is of great importance. Having a reliable light standard, the next important feature is the photometer. A photometer is an apparatus for comparing illumination intensities.

All elementary photometry is based on the assumption of a point source of light and that the intensity of illumination due to the light from a point source varies according to the inverse-square law.

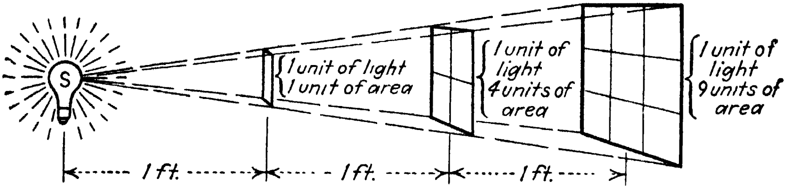

FIG. 5-1.—The law of inverse squares.

Inverse-square Law.—That the intensity of illumination produced by a point source varies inversely as the square of the distance from the source is familiar to all students of science, and the simple methods of photometry are elements of common knowledge but a brief review at this time may not be out of place. A graphic presentation of this law is shown in Fig. 5-1, where the source of light is assumed to be at S and the rays emitted radially in all directions. It will be seen from this figure that the areas of the surfaces normal to the point, enclosed by the radial lines, vary as the square of the distance from the source, and since the light rays originate at the source the amount of light flux on each surface must be the same. Hence it is obvious that the intensity must vary inversely as the square of the distance from the source.

The question naturally arises as to how extensively the assumption of a point source will apply. This subject was investigated by Hyde[1] for a tubular source and a flat circular disk. It was found that at a distance of five times the length of a tubular source or ten times the diameter of a circular surface source the light may be considered as emanating from a point, as far as appreciable error from the assumption of the inverse-square law is concerned.

In photometering a lamp the illumination on one part of the photometer, varying inversely as the square of the distance from the source, is made equal to that on another part received from some source of known candle power. Then, since the illuminations are equal, it is obvious that the candle-power values vary directly as the square of the distances or

$$I_x = I_s \frac{d_x^2}{d_s^2} \tag{5-1}$$

where I_x and I_s are the candle-power values, and d_x and d_s are the distances from the screen of the unknown and known sources, respectively.

If the *distance between the standard and the screen* be fixed and the candle power be maintained constant, then I_s/d_s^2 becomes constant and

$$I_x = Kd_x^2 \tag{5-2}$$

If the *scale of the distances* be graduated according to the square of the distances the above equation becomes

$$I_x = Kr \tag{5-3}$$

where r is the reading on the photometer scale.

From the equation $I_x = Kd_x^2$ the value of I_x may be easily *calculated by means of a slide rule* in the following manner: Place the zero of the slide on the value of K on the upper or A scale, place the cross hair over the value of d on the C scale, then under the cross hair there will be the value of d^2 on the B scale and the product $Kd^2 = I_x$ on the A scale.

The Photometer.—The photometer in all its modifications consists of a screen and its accessories. The screen either reflects or diffuses the illuminations under comparison and may be observed directly by the eye unaided, or through the agency of some optical train. The light reflected by the screen is always less than the illumination that it receives and may or may not be of the same quality. *Selective absorption* is often utilized whereby reflected light from an appropriately colored surface agrees in color with the compared light. The *sensitiveness of the apparatus* increases with the reflecting power of the screen.

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[1] HYDE, *Bur. Standards Bull.*, vol. 3, p. 81, 1907.

Diffusing screens scatter the light in its transmission through them. They consist of some translucent substance and, like the reflecting screens, reduce the intensity of the light. They may be designed to change the quality of the light by selective absorption. The *sensitiveness of a photometer screen* depends upon its luminous efficiency, which is proportional to the reflecting or transmitting power, as the case may be, of the material of which it is composed. The sensitiveness of the photometer, distinguished from the above, depends upon the least amount of change in light which the observer is able to detect. This amount may vary from 1 part in 60 for a weak illumination to 1 part in 120 for an intense illumination.

Types of Photometers.—There are two general types of photometers:

1. The *stationary photometer* which is usually installed in the darkroom and is used for making accurate measurements of candle-power values.
2. The *portable photometer*, which is built in a compact, light-weight form and may be easily employed for making candle-power measurements under actual commercial conditions or for making illumination measurements or surveys.

Photometric Devices.—The different photometric devices may conveniently be divided into four classes:

1. Those dependent on *visual acuity*, which measure the light by the ability of the eye to detect objects illuminated by it.
2. Those in which a photometrical balance is obtained by the *equality of brightness* of two surfaces, each of which receives light from a different source.
3. Those in which the balance is obtained by contrasting the illuminated surfaces and which are known as *contrast* photometric devices.
4. The *flicker photometer*, in which surfaces lighted by either source are presented to the eye in rapid succession.

The relative merits of these different types of photometrical devices still remain a debatable subject. The choice of any one will many times depend upon the conditions under which it is to be used.

Methods of Obtaining a Photometrical Balance.—Various methods are employed to obtain the photometrical balance, *i.e.*, to produce equal illumination on both parts of the screen. These methods may be enumerated as given below.

1. *By varying the distances between the sources and the screen.* This may be accomplished by moving the comparison lamp, keeping the position of the screen and the test lamp fixed; by varying the position of the test lamp; or by changing the position of the photometric device relative to the two lamps. Reference to the equations at the beginning of the chapter will indicate that calculations are simplified by having the distance between the standard lamp and the screen fixed. This may be conveniently accomplished in darkroom photometry by rigidly coupling the supports of the standard lamp and the photometric device together and by varying their position relative to the test lamp placed at zero on the photometer bars. Of the different methods of varying the intensity of illumination on the photometer screen this method is the most universally applicable; it possesses accuracy, reliability, simplicity, flexibility, and can be easily verified.

2. The *absorbing medium* offers a satisfactory and practical means of decreasing the illumination intensity if it be free from selective absorption. It may be used in connection with the variations of distances and in this way increase the range of the apparatus. It may be placed between the screen and the test lamp if large candle-power values are involved, or between the screen and the standard lamp if low illumination intensity on the screen is desired or if the standard is of too high candle power. In this case the equation mentioned above involves another constant which will be the transmission coefficient of the absorbing media. If the photometer scale is graduated proportional to the square of the distances, Eq. (5-3) will become

$$I_x = \frac{Kr}{k'} = K'r \tag{5-4}$$

if the absorbing medium is between the test lamp and the screen, and

$$I_x = k'Kr = K''r \tag{5-5}$$

if the absorbing material is between the standard lamp and the screen, k' being the transmission coefficient of the absorbing material.

3. The *rotating sectored disk* is one of the most valuable adjuncts in photometrical measurements. The principle of this device as applied to photometry is based on Talbot's law. This law as stated by Helmholtz[1] is as follows:

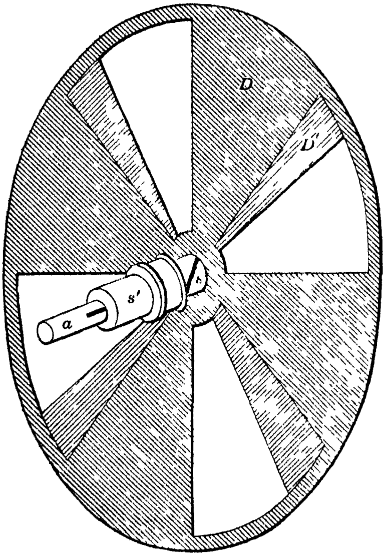

FIG. 5-2.—The sectored disk.

> If any part of the retina is excited by intermittent light, recurring periodically and regularly in the same way, and if the periods are sufficiently short, a continuous impression will result, which is the same as that which would result if the total amount of light received during each period were uniformly distributed throughout the whole period.

The disk may be constructed in several forms. The simplest method of obtaining various ranges by means of the disk is obviously to make a set of disks from some thin material, as sheet metal or fiberboard, having different-sized openings in each. In this way the intensity can be reduced by definite steps from nearly normal value to zero. These different disks may be mounted one at a time on the shaft of a small motor.

It is obvious that a disk, the openings of which could be varied without stopping the motor and changing disks, would be desirable. Such a device is shown in Fig. 5-2. There are two disks, *D* and *D'*, which may be moved relative to each other about the same axis. Both are mounted on the same shaft but on separate sleeves, one sleeve over or outside of the other. By making a spiral slot in one sleeve and a longitudinal slot in the other and by placing a pin through them into the shaft, the size of the openings between the sections of the disks may be easily increased or decreased by sliding the sleeves along the shaft in the proper direction. This change in adjustment may be made while the disk is in operation by placing the end of a lever in the groove of the collar *c* which is attached to the sleeves. The other end of the lever may be placed above a scale calibrated to indicate by the position of the lever the value of the openings in the disk. With this arrangement the intensity can be varied only through a range of about 50 per cent.

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[1] HELMHOLTZ, *Phil. Mag.*, ser. 3, vol. 5, p. 321, 1834.

The minimum speed of rotation is that at which no flicker effect is experienced. Higher speeds give the same results.

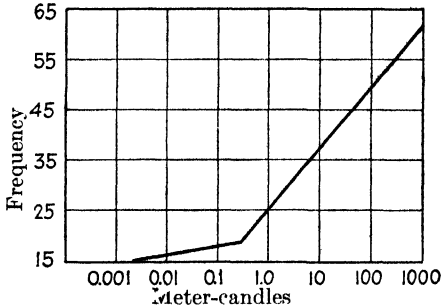

FIG. 5-3.—Frequency at which flicker becomes perceptible for different intensities of illumination.

It is obvious that where the flicker is produced by a rotating sectored disk, it would be more pronounced than if due to alternating current supplied to the illuminant. Investigations of the critical speed of the disk were conducted by Ferry[1] and Porter[2] where light of known intensity and quality was passed through a rotating sectored disk. The critical frequency, or the frequency at which a flicker was just imperceptible, is indicated by the curve in Fig. 5-3.[3] It was found that the vanishing flicker frequency appeared to be a function of optical intensity alone and independent of the color value of the light.

Porter also found that the critical frequency was a linear function of the logarithm of the intensity. For intensities greater than 0.2 meter-candle,

$$f_1 = 12.4 \log E + 24.9 \tag{5-6}$$

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[1] FERRY, *Amer. J. Sci.*, vol. 44, p. 192, 1892.

[2] PORTER, *Proc. Roy. Soc. (London)*, vol. 70, p. 313, 1902.

[3] *Bur. Standards Bull.*, vol. 5, p. 282, 1908.

and for intensities less than this value,

$$f_2 = 1.56 \log E + 19.6 \tag{5-7}$$

for meter-candles and common logarithms. From this curve it appears that rod vision changes or begins to change to cone vision at about 0.2 meter-candle.

Some photometric devices that have been and are used in this country and abroad are described on the following pages together with the prevailing practice concerning their use and manipulation. A careful study of this portion of the subject and the preceding part of the chapter should give the reader a good working knowledge of the fundamentals of the subject.

The Bouguer photometer is said to be the oldest form of apparatus for comparing light sources. It consists of an opaque reflecting screen with a blackened partition at its center and normal to its plane. The two sources of light are placed one on either side of the partition and their distances from the screen adjusted until the illumination of the screen is the same on both sides of the partition.

Later **Potter** substituted a translucent screen in place of the opaque one, which enabled the observer to place the screen between himself and the sources of light.

The Rumford, or shadow, photometer consists of a white screen with a small rod in front of it. The sources are then placed at distances from the screen such that the shadows due to each lamp are of the same density.

The Ritchie mirror photometer was designed for use between the two sources of light on the photometer bars. Mirrors placed at 45 deg. to the common axis of the sources throw the light from each lamp on a comparing screen supplied with a blackened partition separating the rays from the two sources. The screen and mirrors can be enclosed in a compact sight box constructed so as to be moved along the photometric axis.

In the **Ritchie wedge photometer** mirrors are replaced by pieces of white diffusing material. The sensibility of this instrument is greater if the sides of the wedge make an angle of 20 or 30 deg. with a normal plane, the value of the angle for greatest sensibility depending on the material of the reflecting surfaces. The performance of some of the materials investigated by Trotter[1] which could be used for a Ritchie wedge are indicated in Fig. 5-6. These curves show the relative brightness of the surfaces when viewed from various angles from the normal to the surface or

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[1] *Illum. Eng.* (*London*), vol. 2, p. 79, 1909.

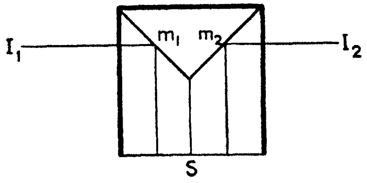

Fig. 5-4.—The Ritchie mirror photometer.

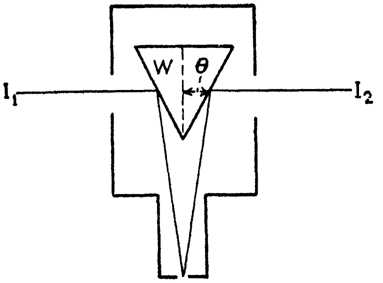

Fig. 5-5.—The Ritchie wedge photometer.

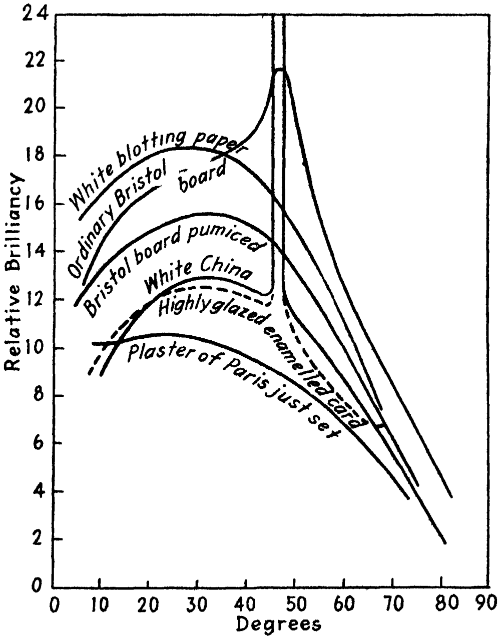

Fig. 5-6.—Effect of changing the inclination of the sides of the wedge (angles measured from normal to the rays).

when they make the various angles with a normal to the rays. Obviously a material similar to white blotting paper makes an instrument of high sensibility and the highest sensibility is obtained by making the angle between the surface and the normal about 30 deg.

It is obviously imperative in the use of photometric devices of this type that the light from the two sources strike the respective sides of the screen at the same angle. Any unequal obliquity of this nature will introduce an error and since the two sides are fixed relative to each other any increase in the obliquity of one side will decrease that of the other and, assuming the cosine law, will double the effect. Referring to the figure it will be seen that the chance of error may be reduced by making the angle of divergence of such value as to give maximum brightness since this point occurs on the flat part of the curve, and maximum sensibility will be obtained at the same time.

The Elster-Joly diffusion photometer involves the use of two blocks of translucent substance as paraffin or milk glass so placed that each receives light from a different lamp. These blocks may be placed side by side with an opaque diaphragm between them. They are viewed from the side and the photometrical setting obtained when both appear equally illuminated by the internally diffused light.

The Bunsen photometer is one of the oldest and simplest forms of photometric devices. Moreover, it is still widely used and constitutes an efficient means of comparing the intensity of luminous sources. The screen differs from those used in the photometers previously described. In its simplest form this screen consists of a sheet of white paper a part of which is made translucent by paraffin or some other similar substance. The transparent portion is usually star shaped, with its edges sharply defined. The light falling on either side of the screen is partly reflected and partly absorbed, while that falling on the treated part is partly transmitted. If the same per cent is absorbed by both parts of the screen, a greater amount will be reflected from the untreated part. When the illumination on both sides of the screen is the same, an equal amount of light is transmitted through the treated portion in each direction, and if the light from each source is of the same hue both sides of the translucent portion of the screen should appear identical. If the same percentage of light is absorbed by both the treated and the untreated portions of the screen, the entire surface of both sides of the screen appears identical when a photometrical balance is obtained, provided the color of the light from the two lamps is the same. The coefficient of absorption of the translucent portion is, however, usually greater than that of the untreated part and a contrast is observed when a setting is secured.

Both sides of the screen are viewed simultaneously by means of two mirrors *mm′* (Fig. 5-7) properly arranged. It is essential that the mirrors have the same reflecting power and make the same angle with the screen. Both sides of the screen are used in obtaining a balance although either or both sides may be used if the absorption of both the treated and the untreated portions is the same. As the screen and the mirrors are reversible, a second balance can be obtained and the mean taken as the result, thus eliminating any error that might arise from dissimilarity in either the sides of the screen or in the mirrors. Referring to the figure, both sides of the screen *ss′* are viewed through the eyepiece *O* by means of the mirrors *mm′*.

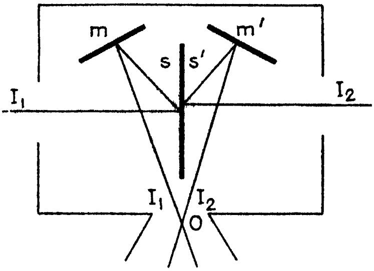

FIG. 5-7.—The Bunsen photometer.

The Leeson disk is an improvement over the Bunsen disk. It consists of a piece of thin, translucent paper with an opaque piece having a central star-shaped opening pasted on either side of it. The edges of the openings exactly coincide on the two sides of the screen. This screen, like the Bunsen, may be of either the contrast or the disappearance type and, since the edges of the translucent portion are more sharply defined than those of the Bunsen, less difficulty is experienced in detecting slight inequalities in the illumination of the two sides of the screen.

The Lummer-Brodhun photometric device consists of a purely optical combination for viewing the two sides of the screen. A diffusing screen *ss′* (Fig. 5-8) of high reflecting power is placed in, and with its plane normal to, the photometric axis. This screen is viewed on both sides by means of the optical device which presents both sides of the screen to the eye as adjacent or concentric fields.

The Lummer-Brodhun photometer is built both as an "equality-of-brightness" and as a "contrast" photometer. The arrangement of each is essentially the same. The light from the two sources, reflected from the sides of the screen *s* and *s′*, falls on the mirrors m_1 and m_2 and is reflected along a normal to the surfaces of the triangular prisms *A* and *B*. The observer, looking through the telescopic tube *O* directed normally to *B*, clearly views a divided field illuminated partly by one source and partly by the other

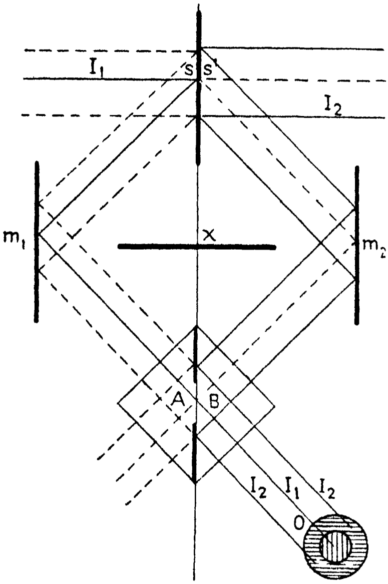

Fig. 5-8.—The Lummer-Brodhun "equality-of-brightness" photometer.

In the *equality-of-brightness photometer* the rays from I_1 pass directly through the central part of the prisms illuminating the central portion of the field as indicated in Fig. 5-8. The rays from I_2 pass in the same way into the prism *B*, the central rays pass directly through the prisms, while the outer rays are reflected by the prism *B* and constitute the outer portion of the field of view. The paths of the light rays viewed through the eyepiece are indicated by the full lines. Those shown dotted from I_1 are reflected by the prism *A* out of the line of vision while those represented by the dotted line from I_2 pass directly through the prisms out of view. With this arrangement a two-part illuminated field is observed, as shown shaded at *O*.

In the *contrast photometer* the principle is the same, but the field is divided as illustrated by the added part of Fig. 5-9. The principle can be readily understood from the previous description. It will be seen that the parts of the field *a* and *d* are illuminated by the source I_1, while *b* and *c* receive light from the source I_2. Two thin pieces of glass *g* and *g′* intercept some of the light illuminating the fields *b* and *d*, thus giving the contrast effect whereby this photometer receives its name. A photometrical balance is obtained when the intensity of *a* and *c* and of *b* and *d* are the same; *a* and *c*, however, will be brighter than *b* and *d*

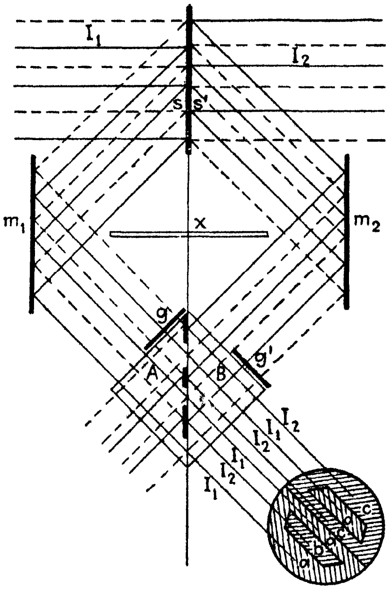

FIG. 5-9.—The Lummer-Brodhun "contrast" photometer.

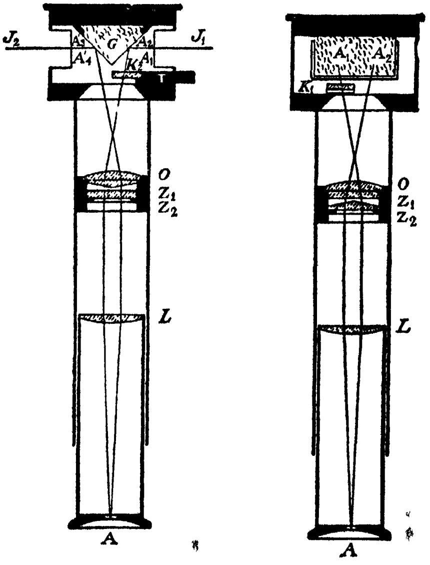

FIG. 5-10. FIG. 5-11

FIGS. 5-10 and 5-11.—The Bechstein photometer.

because of the small amount of light absorbed by the two pieces of glass g and g'.

The Bechstein photometer[1] is shown in Figs. 5-10 and 5-11. This photometer can be used as either a contrast or an equality-of-brightness instrument. It has a Ritchie wedge of plaster of Paris G which receives the light from the two sources and which is viewed through the telescopic combination, as shown. Two biprisms located at Z_1 and Z_2 at right angles to each other present the illuminated fields in the shape of four quadrants, alternate ones of which are illuminated by the same lamp. The angles of the prisms are so adjusted that the prism Z_1 with its dividing edge vertical, divides the field into two equal portions, the left portion being illuminated by the light from the right-hand side of the wedge and the right portion receiving light from the left-hand side of the wedge. The influence of the prism Z_2 is the same as Z_1 except that it is 90 deg. displaced. The result is that the field of view is divided into four quadrants, with opposite quadrants illuminated by the same source. In the equality-of-brightness photometer the photometrical balance is obtained when the four quadrants are of equal brightness. In the contrast photometer the contrasting element may consist of two thin squares of glass K_1 and K_2 inserted in the path of the rays illuminating adjacent quadrants. This glass absorbs a small amount of light, the right amount to produce the desired contrast.

Heterochromatic Photometry.—It has already been shown that the luminous value of a light depends upon its spectral composition, and to some extent upon its intensity. Hence it is obvious that the comparison of the luminous qualities of two lamps differing in color becomes complicated at once. Also it has been found, as might be inferred from previous study of the eye, that a photometrical setting depends upon the size of the retinal area employed or, what amounts to the same thing, the size of the photometrical field.

Sources of light showing but slight color differences can be compared by any of the ordinary methods with an accuracy sufficient for commercial purposes. But when comparing lights differing greatly in color it is the general experience that different kinds of photomoters give different relative values for colored lights. Even the same photometer used in two different ways, or comparing the lights at two different intensities on the screen, or viewing the screen from different distances may fail to give concordant results. Comparisons repeated on succeeding days by the same observer are likely not to agree with those at first obtained, and, what is still worse, the general conclusions reached by one observer are likely not to concur with those derived by another.

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[1] *Illum. Eng.* (*London*), vol. 1, p. 498, 1908.

The Flicker Photometer.—The flicker photometer has been designed for comparing lamps emitting light dissimilar in color, by presenting to the eye surfaces illuminated by each light source in rapidly alternating succession. Its principle is based upon the investigations of Rood,[1] who discovered that when two surfaces differing in color are presented to view alternately and in rapid succession the sensation of color disappears, or the color sensations are combined and the color difference is lost, although the sensation of flicker may persist. Rood also found that when these two surfaces were equally illuminated no sensation of flicker was experienced.

Moreover, the rapid alternations—presenting first one and then the other illuminated surface—tend to exercise the eye at its maximum sensitiveness, and so should reduce the personal variable. This seems verified by the results of experiments, which show that this type of apparatus can be used for comparing light sources presenting the widest contrast in color with a consistency approaching that of the ordinary types of photometers when balancing lights of the same color. Such results are obtainable only with the normal eye, the fatigued eye showing a differential sensibility toward one of the lights.

In the active part of the retina occurs what is sometimes referred to in photometry as the *yellow-spot effect*, the "yellow spot," or fovea, being the small central region of the retina. It will be remembered that the cones are the predominating light-perceiving organs in this region, and that it is at this point that greatest sensibility is obtained. With this point in mind, together with the other peculiarities of the eye previously discussed, it will not be surprising to find that the readings obtained by photometers when comparing different colored lights may depend, within certain limits, upon the size of the photometrical fields, or, what amounts to the same thing, the distance of those fields from the eye of the observer. Investigations of this nature, obviously involving low intensities, by Dow[1] show quite appreciable differences in readings due to these causes.

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[1] ROOD, *Am. J. Sci.*, vol. 46, p. 173, 1893.

Another disturbing factor in heterochromatic photometry is known as the *Purkinje effect.* It appears that the normal eye can distinguish details better in and is more sensitive to light of a greenish or bluish hue when the illumination is of low intensity, while the greenish-yellow hue becomes more efficacious when cone vision comes into prominence and at higher illumination intensities. An investigation of the ratio of ruby-red to signal-green light, two colors distinct enough in color to show the Purkinje phenomenon effectively, by Dow,[2] shows that this factor becomes negligible at ordinary and high intensities.

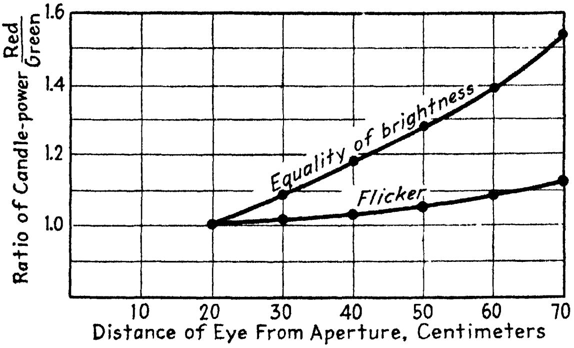

FIG. 5-12.—Comparison of "yellow-spot effect" in flicker and equality-of-brightness photometers.

The flicker photometer appears to be influenced less by the yellow-spot and Purkinje effects than the equality-of-brightness photometer, although it is less sensitive at low intensities. Comparative results showing this as obtained by Dow are shown diagrammatically in Figs. 5-12 and 5-13, where the ratios of the apparent candle power of ruby-red light to signal-green light are given for the two classes of photometers. The wedge arrangement was used. Precautions were taken, for the yellow-spot effect, to ensure the use of the same portion of the retina for each instrument at successive distances from the screen. The retinal area, of course, decreased as the distance increased. For obtaining the results shown in Fig. 5-12 the intensity on the screen remained constant.

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[1] Dow, *Illum. Eng. (London)*, vol. 2, p. 610, 1909.

[2] Dow, *Elec. World*, vol. 55, p. 465, 1910.

In Fig. 5-13 a comparatively large retinal area was used to secure greater sensibility and was of the same size for both photometers. It will be seen that with the equality-of-brightness method the values of the red light in terms of the green light become much less as the intensity of illumination is reduced, which is in agreement with the Purkinje effect, but with the flicker arrangement these ratios show no marked variation in value.

These physiological peculiarities arising from the use of the two types of photometers mentioned above have been verified, qualitatively at least, by several investigators. They indicate that, where low intensities of illumination differing in color *must* be compared, the flicker photometer will yield results less influenced by the yellow-spot and Purkinje effects than will the equality-of-brightness type of photometric apparatus.

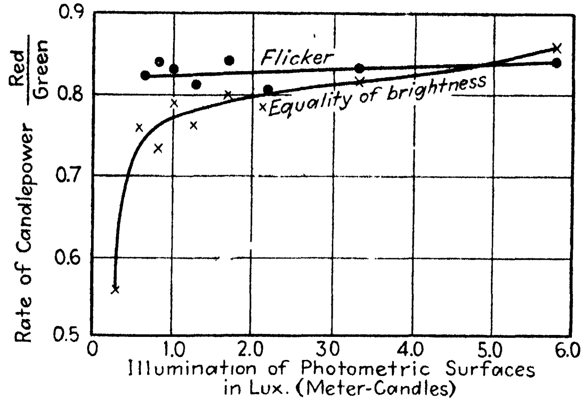

FIG. 5-13.—Comparison of Purkinje effect for flicker and equality-of-brightness photometer.

The discrepancies in results obtained by different observers when different-colored lights have been compared at high intensities have often been attributed to the Purkinje and yellow-spot effects, but it has been proved quite conclusively that these disturbing influences occur only at low intensities.

Bell[1] has shown that errors in heterochromatic work, with the equality-of-brightness photometer and at intensities above the range of Purkinje effect, are the direct effect of *simultaneous*

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[1] BELL, *Elec. World*, vol. 59, p. 201, 1912.

contrast which modifies the apparent luminosities of two colored lights under comparison. When red and green, for example, are in juxtaposition, the red appears redder and the green greener to a very noticeable degree if the circumstances are favorable. According to Titchener,[1] the increase in this contrast effect is always in the direction of the greatest opposition in colors. It increases with the saturation of the more prominent color and is always greatest when there is no simultaneous brightness contrast. The contrast is also sharper if the two colored surfaces are very close, and not separated by visible boundary lines.

The *effect of simultaneous contrast* may be seen by placing a greenish light source, a mercury arc, for instance, on one end of the photometer bars on which is mounted a Lummer-Brodhun screen. When observed through the eyepiece the field appears a faint bluish white similar to the color of the tube. If the mercury lamp is extinguished and the other side of the screen illuminated by a carbon lamp, the field will appear the usual yellowish white. But if both lamps are lighted, the sides of the screen become at once a conspicuous green and a brilliant orange, neither in the least resembling the color when either was used by itself. Hence it will be seen that due to contrast two colors in juxtaposition may be changed in hue to a surprising degree and abnormally thrown apart in the spectrum. Bell suggests Fig. 5-14 as conveying an approximate idea of what happens in such a case. Suppose two lights of the spectral regions a and b are being compared. When thrown on the screen in juxtaposition the hues are changed by contrast so that the red becomes redder and the green greener. The contrasts therefore correspond to colors of lessened luminosity, but lessened in unequal degrees, as, for instance, a shifting to a' and b to b'. The red is decreased relatively more, and a photometrical balance based on the contrast values would show an apparent Purkinje effect at illumination intensities much higher than those within which the real Purkinje effect comes into play.

As illumination intensities are greatly increased, even spectral colors become relatively less saturated and would consequently affect each other less by simultaneous contrast. As the lower limit of color vision is approached, on the other hand, the effects of contrast are less conspicuous, so there is a gradual transition into the actual Purkinje effect when the intensity is reached at which rod vision is dominant.

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[1] TITCHENER, *A Text-book of Psychology*, p. 76.

In ordinary illuminants the red side of the luminosity curve is somewhat steeper hence an equal shifting of two contrasting colors would be of the nature explained above. In view of these conditions it is probable that a large proportion of the aberrations found between different observers, and by the same observer at different times when using the equality-of-brightness photometers, are mainly due to the phenomena here described.

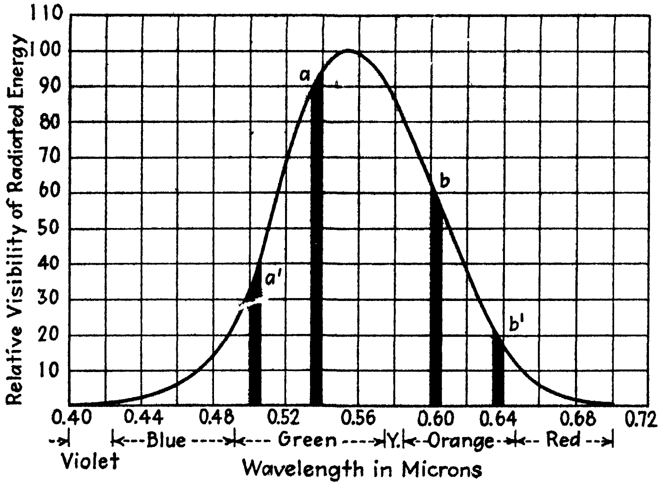

FIG. 5-14.—The suggested effect of comparing colors in juxtaposition.

The flicker photometer eliminates simultaneous contrast. The color flicker disappears before the brightness flicker, and when the balance is actually determined by the disappearance of the latter the colors have blended into a combination of the two from which simultaneous contrast has disappeared.

Color difficulties can also be reduced in the Bunsen or Leeson screens by making the central portion of the field of such thin, translucent material that there will be a marked color blending there, which will greatly reduce the color contrast.

The concluding paragraph of Bell's article[1] follows and sums up the question of the choice of photometer for color photometry as far as color contrast is concerned.

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[1] BELL, *op. cit.*

In making a judgment of brightness such as has to be made in an equality-of-brightness photometer the eye can depend only on what it sees and therefore makes its judgment on the apparent colors which it sees as influenced by contrast. Hence, if the contrast is of such a character as to shift the effective luminosities of the two color fields by unequal amounts, a color error will be introduced in the setting, and since the red side of the luminosity curve is usually steeper than the green side, the net result in comparing colors is often to produce a spurious Purkinje phenomenon perceptible even at fairly high illuminations. Even when this effect does not exist, the shifting of colors by contrast along the luminosity curve still takes place, and since different observers and the same observer at different times vary in perception of simultaneous contrast, small and shifting color errors are constantly introduced in photometric observations which bear no relation to the genuine Purkinje phenomenon or to the absolute color sense of the individual observer. Perhaps the strongest claim of the flicker photometer rests on its freedom from errors of this kind, due to the fact that color blending is secured at a lower frequency than corresponds to the disappearance of brightness flicker, and in fact the flicker photometer is the only form in which simultaneous contrast is fully eliminated, which is another good reason for employing it in heterochromatic comparisons.

A series of researches by Ives[1] are of great value in solving the problems in heterochromatic photometry. In these investigations Ives used the flicker and equality-of-brightness arrangements for obtaining the luminosity curves showing the comparison of the spectral colors with white light. The apparatus was so designed that it could be used for the equality-of-brightness and the flicker methods without disturbing any critical conditions.

The illumination used was 250 units, where a unit is the illumination of 1 meter-candle on a surface of magnesium oxide as viewed through an artificial pupil of 1-sq. mm. area. Because of the small area of this pupil opening, the effective illumination was probably about one-tenth of these values. A circular photometrical field 16 mm. in diameter at 24 cm. from the eye was chosen. This field subtended an angle of 4.5 deg., approximately the size of the yellow spot of the retina.

Readings were taken with each type of photometer for 12 points in the spectrum alternately on the red and on the green sides. The average readings of five observers at the high intensity of 250 units are shown by the curves of Figs. 5-15 and 5-16. It will be seen that the average of the readings of the five observers, shown by the full lines, are practically coincident for the two types of photometers. It will be seen, however, that there is considerable variation among the different observers when using the equality-of-brightness type. It should be remembered here that the different colors were being compared with white, thus giving less degree of contrast than the cases previously cited, and also the two fields were not in exact juxtaposition. At low intensities (10 units) the luminosity curves obtained by the equality-of-brightness method shifted toward the blue end of the spectrum according to the Purkinje effect, whereas the luminosity curves obtained by means of the flicker device shifted toward the red end of the spectrum, this latter result being hitherto unobserved. The conclusion drawn from this investigation is that the flicker photometer should not be used for comparing low intensities, as the results so obtained must necessarily be incorrect. For comparing high intensities it may be expected that the results obtained by the two methods may possess approximately the same degree of accuracy. At high intensity it was found that the flicker arrangement showed far greater sensibility and there

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[1] IVES, *Trans. Illum. Eng. Soc.*, vol. 5, p. 711, 1910.

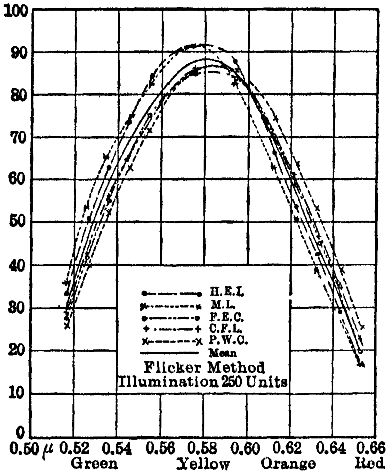

FIG. 5-15.—Relative luminosity of monochromatic light (flicker method).

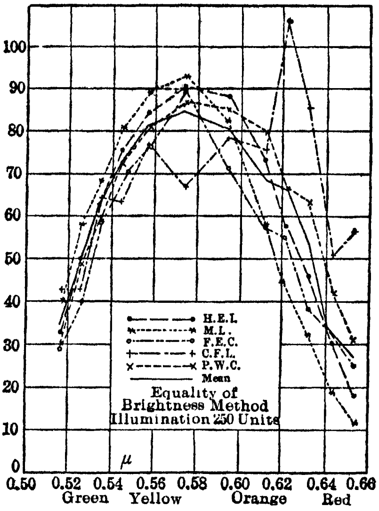

FIG. 5-16.—Relative luminosity of monochromatic light (equality-of-brightness method).

were fewer variations in the readings of different observers. These points of merit, together with the greater ease of obtaining a photometrical setting and the less liability of change of the observer's criterion, point to a decided superiority of the flicker photometer for heterochromatic photometry.

Heterochromatic photometry is still a debatable subject, however, and these investigations may be considered as preliminary steps in the solution of the problem as a whole. Quoting Ives[1] where, in referring to the general coincidence of the luminosity curves obtained by the two methods at high intensity, he states:

> This then would be an argument for choosing such an illumination as the standard one for making the heterochromatic comparisons necessary for the preparation of standards of different colors. For it must be clearly borne in mind that such comparisons can, from the nature of vision, hold exactly for only one illumination and size of field. The best solution to be hoped for must contain specifications of these two conditions. When the stage has been reached where one can give a definite candle-power rating to a colored illuminant for a certain illumination the first step will have been made. The second step will be when one can state also what the illuminant's candle power will be at any other illumination, knowing it at the standard.

The Whitman Flicker Photometer.—One of the earliest flicker photometers was made by Whitman. Its construction is illustrated in Fig. 5-17. The disk *BD*, constructed as shown at the left, revolves around its axis *A*. When in the position shown at the right it presents to the eye of the observer at *O* a surface illuminated by I_1. When *B* has turned from a position in front of the eyepiece the observer sees the surface *C*, which is illuminated by light from I_2. In this way, by rotating the disk *BD* at its proper speed by means of a small motor or similar device, the two illuminated surfaces are presented to the eye in rapidly alternating succession, and a balance is obtained by varying the intensity on one surface or the other, as in the ordinary type of photometer head.

The Simmance-Abady flicker photometer consists essentially of a thick disk of plaster of Paris driven by a clockwork mechanism. The edges of the disk are beveled, as shown in Fig. 5-18, and these beveled surfaces are viewed from above as they revolve by means of a 45-deg. mirror or prism and the sight tube, as shown in Fig. 5-19. It will be seen from the construction of the disks that the observer sees first a surface illuminated by one lamp and then a surface illuminated by the other, presented alternately and in rapid succession when viewing the disk through the sight tube and the prism. The speed of the disk can be adjusted by a regulator until highest sensibility is obtained. This adjustment is simple and offers no difficulty.

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[1] IVES, *op. cit.*

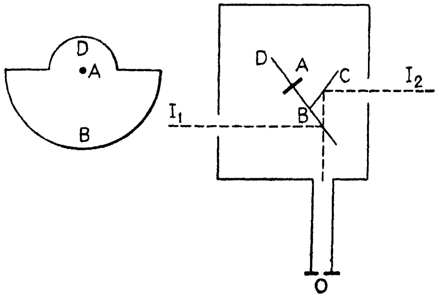

FIG. 5-17.—The Whitman flicker photometer.

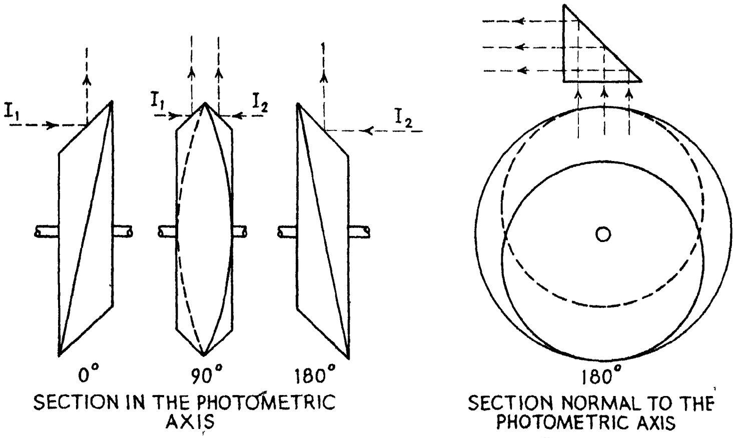
I1
I1
I2
I2
0°
90°
180°
SECTION IN THE PHOTOMETRIC AXIS
O
180°
SECTION NORMAL TO THE PHOTOMETRIC AXIS

FIG. 5-18.

FIG. 5-19.

FIGS. 5-18 and 5-19.—The Simmance-Abady flicker photometer.

The Bechstein flicker photometer[1] is of the type in which a lens oscillates in front of the dividing line between the illuminated surfaces in the photometer. The optical arrangements are shown diagrammatically in Fig. 5-20. The two sides of the wedge *G* are illuminated by the two sources of light. The path of the rays from the photometric surfaces to the eye is through the lens L_1, through the prismatic arrangement *Kk*, to the eyepiece at *A*. The prismatic arrangement *Kk* consists of a prismatic annulus *K* the angle of which is so chosen that, in the position shown, only the rays from the right side of the wedge are brought to the eyepiece. Within the annulus *K* is fixed the disk *k*, which is likewise prismatic, having an angle of inclination equal, but in the reverse direction, to that of the annulus. Consequently, only the rays from the left side passing through this disk are brought to the eyepiece. The result is that the eye sees a field of view consisting of a circular area inside of an annular area. The inner area is illuminated by rays from the left-hand source, and the outer ring by means of rays from the right-hand source. If the prismatic arrangement *Kk* is kept stationary, we can employ the photometer on the equality-of-brightness principle and obtain a balance by judging when ring and center appear equally illuminated. In order to obtain the flicker, the prismatic disk *Kk* is rotated about a horizontal axis by means of a band from a small motor passing over the pulley *R*.

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[1] *Illum. Eng. (London)*, vol. 1, p. 499, 1908.

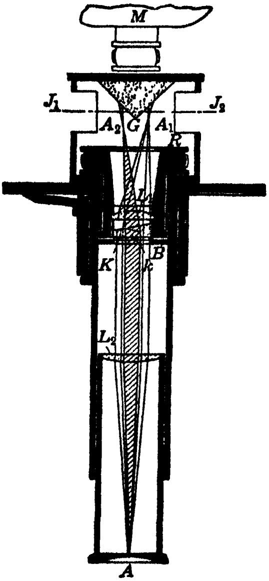

FIG. 5-20.—The Bechstein flicker photometer

The Speed of a Flicker Photometer.—In practice little difficulty is experienced in obtaining the proper speed of the flicker photometer. This speed should be the minimum at which flicker can be made to disappear when a balance is obtained. In other words, the proper speed is that at which a flicker is most perceptible in a slight unbalancing, but imperceptible when a balance is secured.

The Cascade Method.—In photometering lamps differing in color as in the color range of incandescent lamps the step method may be used to reduce the possibility of error. As an illustration, we wish to photometer a 200-watt tungsten lamp emitting 17 lumens, having as a standard a carbon-filament lamp of some 4 or less lumens per watt. The procedure would be to interpose some substandards of intermediate lumen values dividing the color difference into a number of smaller color differences not sufficient to introduce color errors when photometered with the equality-of-brightness or the contrast photometer.

The new gas and vapor lamps have introduced new problems for the photometrist because of the color differences of their light one with another and with the accepted standards.

Filters.—The most satisfactory method of measuring the candle power of such lamps as the sodium, mercury, and neon lamps appears to be by means of color filters on the comparison or standard incandescent-light source making a color match with the test lamp. The filter, usually of colored glass, must have proper spectral transmission and its absorption coefficient must obviously be known. To measure the luminous output of a sodium lamp a yellow filter may be used.

Sodium colored standards have been developed for measuring the luminous intensity of sodium lamps.[1] These standards were constructed by placing a 1,000-watt filament in a 300-watt medium amber bulb, the bulbs being so selected as to color that when the filament, rated at 115 volts, was operated at 80 volts the color, to the eye, matched that of the sodium lamp. Before being used each of these standard lamps was immersed in water and operated for 1 hr. at 125 volts for seasoning.

The sodium standards were measured by comparing them with clear standards in a globe photometer. The color difference was eliminated by using a dense amber filter in front of the clear standard. It was then necessary only to know the transmission factor of the filter and the integrating factor of the sphere for the clear standard and for the sodium standards.

A filter of known characteristics is necessary only for calibrating the lamps. After calibration the sodium standards can be used in a globe photometer for testing sodium lamps with any filter which gives a satisfactory color at the back or comparison lamp.

In the case of the mercury lamp comparisons *can* be made directly between a high-pressure mercury lamp and a 500-watt incandescent lamp standard but no very accurate results can be obtained with this color difference. Two filters are necessary in matching colors with these lamps.[1] The blue lines of the mercury offer trouble with a green filter only. This was overcome by using a green filter in front of the incandescent lamp and a yellowish filter, which absorbed the blue rays, in front of the mercury arc. This procedure obviously requires two corrections.

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[1] BENFORD, *Gen. Elec. Rev.*, vol. 37, p. 342, 1934.

A neon-gas-discharge lamp can be very well matched as to color by the use of a selected red glass in front of the comparison lamp.

Physical Photometry.[2]—The many difficulties and chances of error in visual photometry, *e.g.*, the uncertainty of measurements when large color differences are encountered, the variation of the readings of the same individual from day to day, errors due to eye fatigue, etc., have long made desirable some sort of physical photometer so that the determination of the intensities of light sources could be made without depending for final judgment upon so unreliable a measuring instrument as the human eye.

To construct a physical photometer that will function properly under all conditions requires a radiant-energy-measuring device that will weight luminous radiation wave length by wave length in just the same way as the average eye does under the various conditions of exposure to radiations of different intensities. Due to the variation of the sensibility of the eye at low illumination intensities (rod vision) such a device for all ranges of intensities is practically impossible. For luminous intensities above this certain low value the relative sensibility of the eye for radiation of different wave lengths is found to be quite constant. Since the wave-length calibration curve of the eye is known, it should be possible to produce an energy-measuring device which alone or in combination with filters would have a response curve of practically the same shape as the average visibility curve of the eye.

The Photoelectric Tube Photometer.—If an attempt were made to measure the light intensity for the entire range of light sources—natural, incandescent, and the gaseous and vapor sources—the wave-length sensitivity curve of the apparatus must be nearly the same as the visibility curve. However, if only the luminous radiation of incandescent lamps is to be measured or compared a close agreement is not necessary.

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[1] FORSYTHE, *Trans. Illum. Eng. Soc.*, vol. 31, p. 181, 1936.

[2] *Ibid.*

Naturally attention should have been directed to the photoelectric tube as a possibility for measuring apparatus. As yet tubes with a wave-length sensitivity curve entirely satisfactory for this purpose have not been developed. However photometers have been developed using the photoelectric tube as the measuring device. These are proving satisfactory for measuring the candle power of and illumination from incandescent lamps when properly designed for the purpose.

For some time practically all the measurements of the light output of incandescent lamps made in the laboratories of the incandescent-lamp factories in this country have been made with photoelectric tube photometers attached to Ulbricht spheres. By the use of this type of physical photometer three very great advantages were obtained for the industrial laboratories: (1) the measurement of the output of the incandescent lamps did not depend upon a selected group of trained observers. (2) An increased accuracy in the relative measurements for any one type of lamp; (3) increased speed of operation. With this limited physical photometer an operator at the sphere can compare any one type of incandescent lamp with the proper standard as accurately as, or in many instances more accurately than, was possible in the standardization laboratories by eye observation. Also these operators are able to compare a number of standards of any one particular type more accurately than indicated by the values assigned to individual standard lamps by the standardization laboratory, and thus at times they have assigned and used values for the individual lamps, in terms of the average of a large group, that differ slightly from the value assigned by the standardization laboratory.

The Precision Photometer.—Where candle-power measurements of the *highest possible accuracy* are required, as in obtaining the value of the intensity of lamps to be used for secondary standards, in research work respecting the performance of illuminants, in making measurements likely to become the basis of litigation, or, in fact, in any photometric work where a high degree of accuracy is required, recourse should be made to the darkroom and the standard bar photometer. The arrangement of the apparatus and auxiliaries for such measurements are shown

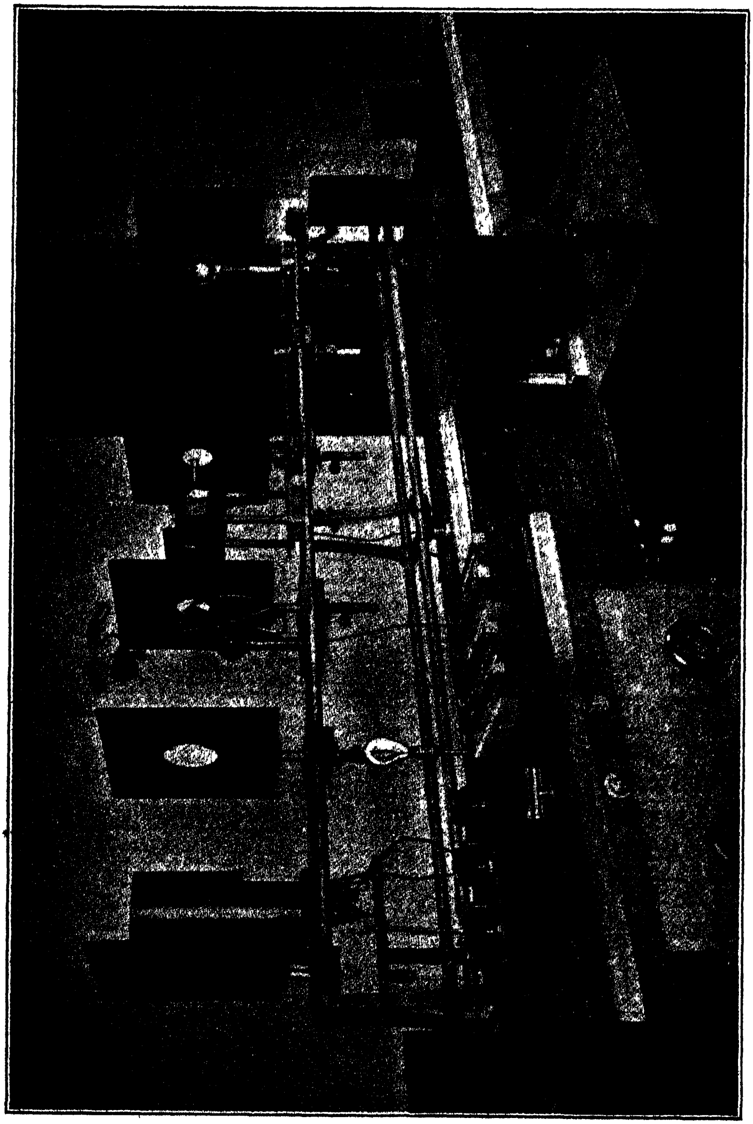

FIG. 5-21.—A complete photometer bench.

in Fig. 5-21,[1] which represents part of the apparatus used for precision measurements at the Bureau of Standards.

For this class of work a room with its walls, floors, and ceiling painted a dull black, and from which all stray light is excluded, is desirable, although a room with light-colored walls may be used if the necessary screening of reflected light is provided and other precautions observed. Having the darkroom, the next item is the photometer. This may consist, as shown in the figure, of two bars of tubular or angular cross section supported on a frame, and the whole device mounted on a bench or table. The standard bars are graduated to read in millimeters and are usually from 2.5 to 4.5 m. in length. These bars support three carriages, two for the lamps and one for the photometric device. These carriages are provided with clamps, by means of which they may be kept in a fixed position, and with holders for the lamps and photometer head. These holders may be raised or lowered to place the centers of the light sources and the screen in the photometric axis and at the same distance above the bars. A carriage carrying a lamp may be placed at either end of the bars and the photometric device moved along the bars to obtain a setting, or one lamp may be placed at the zero end of the bars and the photometer head and the other lamp, with their carriages rigidly connected, moved together. This latter method is more convenient since the equation for calculating the results is thereby simplified. In the figure are shown the rheostats for adjusting the voltage impressed upon the lamps, and at the left the potentiometer for determining the correct value of this voltage. The galvanometer is shown against the wall and the translucent scale, on which a spot of light is thrown by the mirror of the galvanometer, may be seen just back of the potentiometer. A rotating sectored disk may be seen in the photometric axis to the left of the photometer screen.

A series of *screens* are shown, the function of which is to intercept the stray light reflected from the walls and ceiling. Those between the two lamps have openings at their centers and they are so placed that the direct rays from the lamps reach the photometer screen unobstructed. These screens may be made of black velvet or of any material painted a dull black. Unless the material of which the screens are made is very thin, the edges around the holes should be chamfered so as not to reflect light onto the photometer screen. Screens should also be placed so that no light will shine into the eyes of the observer.

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[1] *Bur. Standards Bull.*, vol. 2, p. 1, 1906.

Housings are also shown for the two lamps. These, however, are not necessary in a room with dark walls and ceilings, but if used, they should be lined with black velvet or dull-black paint.

Two methods are in vogue for using this apparatus in the photometry of luminous sources, *viz.* the direct and the substitution methods. In the *direct method* the standard is placed on one side of the photometer screen and the test lamp on the other, as may be inferred from the above discussion. When a number of lamps are to be tested, it becomes desirable to check the working standards from time to time and the *substitution method* may be employed. This method may be conveniently carried out by placing the standard lamp at zero on the scale and the comparison lamp in the carriage attached to the photometer head. After checking the candle power and adjusting the voltage of the comparison lamp, the standard lamp may be removed and the test lamp put in its place. This method will be found convenient when the two sides of the photometer screen are not exactly alike since it does away with the necessity of reversing the screen and averaging the readings.

The Recording Photoelectric Spectrophotometer.[1]—This device has been designed for making spectral-reflectance and spectral-transmission measurements of a variety of materials. The material to be examined is placed in the instrument and in a few minutes there will be shown on a chart the amount of light of each wave length reflected or transmitted by the sample. The comparison of charts from different samples shows in what wave lengths their colors differ and shows how and where to make the necessary color corrections.

This instrument consists essentially of a double-prism monochromator, a photoelectric photometer, and a graphical recorder (Fig. 5-22).

The monochromator is of the double-prism type, which ensures a high degree of spectral purity. It is equipped with bilateral slits that are automatically adjusted for a wave-length band of 10 millimicrons.

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[1] *Gen. Elec. Rev.*, September, 1936.

The photometer combines the polarization method of photometry with a photoelectric balancing scheme in a manner that eliminates such possible sources of error as light-source characteristic and phototube and amplifier sensitivity.

The light source is a coiled-filament tungsten lamp (shown at the bottom). The collimator lenses and prism No. 1 produce a spectral image of slit No. 1 in a vertical plane normal to the mirror. The second slit is formed by a slit jaw and its mirror image. Prisms No. 1 and No. 2 are alike and are arranged symmetrically in order to produce at slit No. 3 a pure 10-millimicron band, the wave length of which is determined by the positions of the mirror and of slit jaw No. 2. The mirror and slits are moved by cams that are geared to the drum of the recorder.

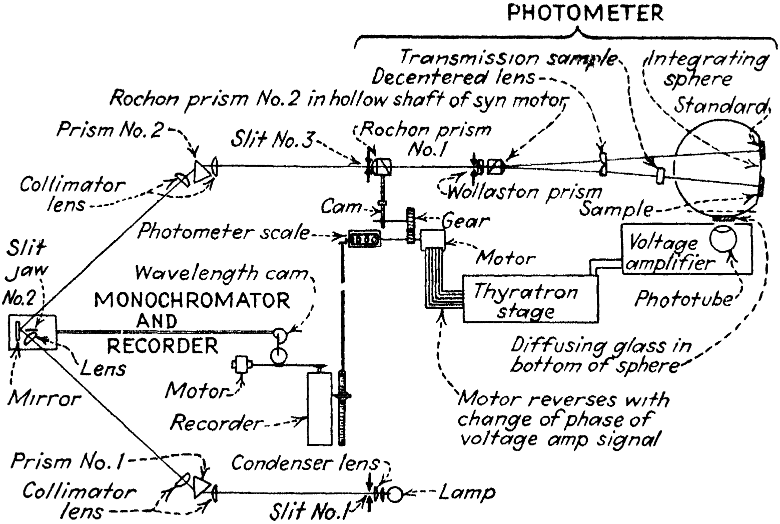

FIG. 5-22.—Schematic diagram of the spectrophotometer.

Monochromatic light from slit No. 3 is plane polarized by Rochon prism No. 1. Two components are generated from this monochromatic beam by the Wollaston prism. These components are mutually perpendicularly polarized and fall upon the standard and the sample, respectively. Rochon prism No. 1 is mounted in a bearing and is rotated by a cam arrangement. The angular position of this prism determines the intensity ratio of the two beams. Rochon prism No. 2 is mounted in the hollow shaft of a synchronous motor. The rotation of this element alternately suppresses and transmits the sample and standard beams, which are always 180 deg. out of phase. This alternation occurs at the rate of 60 cycles per second.

A phototube views an opal glass in the integrating sphere wall, the brightness of which is the sum of the products of beam intensity and reflectance for both sample and standard. When the reflected light from the standard is not the same intensity as that from the sample, an alternating-current component is present in the phototube current. The phase of this alternating component with respect to the voltage applied to the synchronous motor indicates which of the two reflected beams is the more intense. This amplified alternating component is then used to control the direction of rotation of a balance motor. This motor readjusts the Rochon prism No. 1 to obtain a redistribution of energy in the standard and sample beams, thus removing the alternating component in the phototube current. The angular position of Rochon prism No. 1 is then a measure of the reflectance of the sample in terms of the standard.

The illumination on the sample and standard is normal to the surface and covers an area 1 in. in diameter. The opal glass in the integrating sphere wall is symmetrically located with respect to the positions of the sample and standard.

Transmission measurements can be made by using a reflectance sample and standard of the same material, usually magnesium carbonate, and introducing the transmission specimen in the incident sample beam. When duplicate transmission cells are available, provision can also be made for placing a second transmission specimen in the standard beam. Thus if a cell containing a solution is placed on the sample side and a duplicate cell filled with solvent is inserted in the standard beam the intensity difference of the two beams is due only to absorption by the dissolved material.

The characteristic of the light source has no influence on the measurements because both the sample and the standard are illuminated by the same source through an optical system that is common to the sample and standard, with the exception of a pair of decentered lenses which are used to widen the angular deviation between the standard and sample beams. Since the voltage amplifier and the Thyratron tube stage amplify alike the phototube current for the sample and the standard, the measurement is independent of the characteristics of these units. As only monochromatic light reaches the phototube the spectral response of the latter does not enter into the result. With these improvements a higher order of precision has been obtained than was previously possible with instruments of this type.

As the record drum revolves, the wave length of the light reaching the standard and sample is varied at a uniform rate from the red to the violet end of the spectrum.

Since the device is a recording instrument, it does not require the services of an operator with specialized training in optics. Using a phototube, it has ample sensitivity at the violet end of the spectrum, where visual spectrophotometers must fail because of the low visibility of violet light.

One of the most important fields of usefulness for the new instrument is the cataloguing of the curves of different dyes, inks, and pigments, so that new colors with predetermined characteristics can be obtained at any time by the proper mixture of standard colors already at hand.

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CHAPTER VI

PORTABLE PHOTOMETERS AND APPARATUS FOR OBTAINING DISTRIBUTION OF LIGHT FROM A LUMINOUS SOURCE

Much attention is being given to the measurements of illumination in homes, offices, commercial houses, and the industries to ensure adequate illumination for the particular tasks performed therein. Also for providing a check on a new installation, comparing different lighting systems, and securing information necessary to predetermine the details of a lighting installation, illumination measurements or surveys are necessary.

Various types of portable photometers have been designed and constructed for making illumination measurements, and there are several devices for determining the distribution of light from an equipment. These are discussed on the following pages and a careful study of the use and manipulation of the different types of apparatus should equip the reader with a practical knowledge of this part of the subject.

The principles of portable photometry are essentially the same as those of ordinary photometry discussed in the preceding chapter. They make use of some one of the photometric devices there described, and can, in general, be used for candle-power measurements with possibly a less degree of accuracy. Several methods may be employed for obtaining a photometrical balance. Some of these are as follows:

1. Varying the distance between the comparison lamp and the screen.
2. The use of absorbing media.
3. Dispersion lenses.
4. Variable diaphragms.
5. Polarization media.
6. Inclination of the illuminated surface.
7. Variation of the intensity of the comparison lamp.
8. Combinations of two or more of the foregoing methods.

The most accurate and generally satisfactory system of obtaining a balance is the combination of the first and second methods. The *absorbing medium* is used to increase the range of the instrument or to approach a balance by definite known steps, while the *variation of the distance* between the screen and the comparison lamp is used for a gradual approach and for obtaining the final setting.

In making illumination measurements a *test plate*, consisting of a plain, white surface, is used to receive the illumination to be measured. To give high sensibility to the apparatus, this plate should be made of material having a high coefficient of reflection and should possess a high diffusing quality, so that the intensity received from an angle will obey the cosine law. The plate should be made of material that will not introduce errors due to selective absorption and it should be so placed that neither the instrument nor the observer will intercept any of the light rays which would and should fall upon it. Furthermore the instrument should be so designed that the test plate can be placed at any angle in a vertical plane passing through its center. The test plate may be of translucent material and viewed from the rear. The same specifications as to freedom from selective absorption and to diffusibility apply also to this type of test plate.

The *ideal photometer* should possess a test plate of plain, white diffusing substance, the most reliable comparison source of light and the best means of varying the intensity of light admitted to the comparison device, thus making a photometrical device of highest sensibility. For making light surveys and for measuring illumination in general, portability becomes of importance, and a direct-reading scale whereby the values of illumination or candle power, as the case may be, are indicated by the photometrical setting without calculation will be found a great convenience.

The manipulations of a portable photometer for illumination, candle-power, or brightness measurements are discussed in the following pages. Various types of photometers employing the different methods of obtaining a photometrical balance are also described.

A portable photometer that has been extensively used in this country is known as the **Sharp-Millar universal photometer.**[1] This instrument represents the endeavor of the inventors to embody in one piece of apparatus the features which characterize the ideal photometer, *viz.*, a sensitive photometric device, the best means of obtaining a photometric balance, adaptability to the use of a reliable source of light for a comparison standard, portability, and simplicity of operation. A further requirement for the measurement of illumination is a proper test plate to receive the illumination to be measured. Such a plate should have a surface of sufficient diffusibility so that its illumination varies according to the cosine law and should be so located that neither the instrument nor the operator will intercept any light which would otherwise fall upon it. With due regard to these features the photometer was constructed as shown in Fig. 6-1. For a sensitive photometric device a modified form of the Lummer-Brodhun arrangement of the comparison-of-brightness type was adopted and located at *B*, where it is viewed through a telescopic eyepiece in the side of the box. The *photometrical balance* may be obtained by varying the distance between the comparison lamp *C* and the screen. An electric lamp was chosen for the comparison source, as would naturally be expected, and either a low-voltage lamp of the battery type or one of higher voltage to receive power from the service mains may be employed. When a battery lamp with a tungsten filament is employed, it has been found convenient to use primary cells for the source of power and to maintain the intensity of the standard constant by means of a low-reading ammeter. Then by the use of lamp cord or similar conductors the photometer may be used to measure the illumination over a considerable area without having to move the meter and battery. Portability is ensured by constructing the body of the instrument of wood and minimizing the number of detachable parts.

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[1] *Elec. World*, vol. 51, p. 181, 1908.

A side elevation of the photometer is shown in Fig. 6-1. The comparison lamp is located at *C* and can be made to slide along a track, running lengthwise of the box, by means of a cord which is attached to the supports of the lamp and passes through pulleys and around a drum which is operated by the knob *D*. The light from this lamp falls upon a milk-glass plate at *K*, which is viewed through the optical device. The intensity of light upon this plate is made to vary inversely as the square of the distance from the comparison source by making the inner surface of the instrument a dull black and by interposing a system of moving screens. These screens are of fiber, supported on brass rods, and have apertures of sufficient size to permit the direct rays from the lamp to pass unobstructed. At the same time they are of sufficient size to intercept any light reflected from the sides of the box.

The scale upon which the indications of the photometer are read is made of translucent celluloid, graduated with an inverse-square scale, and placed in a longitudinal opening in the side of the box. This scale is equipped with a shutter which may be lowered or raised by means of an external knob and which may be used to exclude external light from the interior of the box. To facilitate taking readings in dark places, a slit is cut in the side of the housing containing the comparison lamp, so that when the shutter is raised the shadow of the pointer, which is inside the box, is cast upon a brightly illuminated scale. On the other side of the housing is a small tube and cross hair, which, when the comparison lamp is properly placed, throws a line in the middle of a spot of light on the side of the box. In this way the proper position of the lamp is determined.

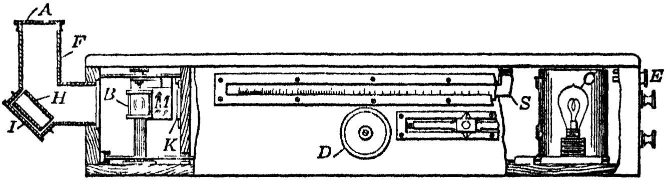

FIG. 6-1.—Side elevation of Sharp-Millar photometer.

Beneath the scale and toward the right of Fig. 6-1 is shown a resistance for varying the current of the lamp. At the rear end of the box are four terminals, two for the supply line and two for the voltmeter, if one is used.

The elbow tube at the end of the box has a number of important functions. It fits friction-tight on a collar fastened in the end of the box and hence may be turned about a horizontal axis and set at any angle, which angle is indicated on a semicircular scale on the end of the box. In the elbow of the tube is fixed a reversible plate, one side being a diffusely reflecting surface used in the measurements of candle power, and the other a mirror used in connection with a test plate on the end of the tube for measuring illumination. In measuring candle power, the diffusely reflecting surface is turned toward the inside of the tube and the end of the elbow tube is open, the tube serving to screen the plate from stray light. The distance between the plate and the source of light must be known.

The photometer being portable and the elbow tube adjustable to any angle, this arrangement lends itself to determinations of the vertical distribution of luminous intensity of light sources, and is also applicable to the measurement of the candle power of street lamps, either close at hand or at a considerable distance from the lamps.

To measure general illumination, the translucent illumination test plate is slipped onto the end of the tube and the plate at the elbow is reversed, making its mirrored side effective. The illumination on any required plane can then be measured, as the light has unobstructed access to the test plate.

It has been found to be most convenient to make the scale direct reading in foot-candles. The same scale is equally applicable to the measurement of illumination and of candle power. The foot-candle scale in question has a range of from 0.4 to 20 foot-candles. This range can, of course, be increased by the use of absorbing screens. Two such screens are used, one of which transmits substantially 10 per cent of the light falling upon it while the other transmits only 1 per cent of the light. By turning the knurled head, which is exposed when the cover of the photometer box is lifted, either screen may be interposed between the prism and the milk-glass window, or between the prism and the elbow tube, or both screens may be turned to such a position that they intercept no light. Evidently, when the screens are used, the total range of measurement, with but one comparison lamp, is from 0.004 to 2,000 foot-candles, within which range all measurable lights and illuminations can be said to fall. It is to be understood, of course, that the coefficient of absorption of these screens must be determined exactly by measurement.

To properly calibrate the instrument for the measurement of candle power or illumination, a known candle power or illumination produced by a standard lamp should be employed. The voltage or the current of the comparison lamp is adjusted by means of the slider rheostat on the box to such a value that the pointer on the scale indicates the known candle power or illumination. The instrument then becomes direct reading for candle power or illumination, as the case may be, all effect of lack of symmetry, etc., being eliminated.

The Macbeth Illuminometer.—The photometric principle of this instrument is the same as that of the Sharp-Millar photometer. It has a Lummer-Brodhun-type photometrical device and uses a low-voltage lamp as a comparison lamp. In operation the comparison lamp is moved back and forth on the optical axis until a balance is observed through the telescope. It has a scale calculated according to the inverse-square law and calibrated to read foot-candles direct. The construction is indicated in Fig. 6-2. The photometric field is viewed through the telescope *C*.

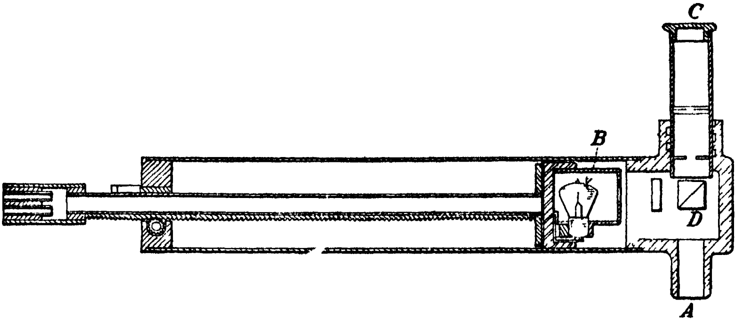

FIG 6-2 —Section of Macbeth illuminometer tube.

The aperture *A* opposite the telescope is pointed toward the test plate, or any surface the brightness of which is to be measured. In the tube, which is 9 in. long by $1\frac{3}{4}$ in. in diameter, is a diaphragmed carriage within which is mounted an electric incandescent lamp. The lamp carriage is moved in the tube by means of a rack and pinion operating upon a square rod to which the carriage is fastened.

The test plate is made of white glass finished by a special process to give it good light-diffusing properties.

Compensated Test Plate.—No surface has been found which reflects or transmits light in strict conformity to Lambert's cosine law, *i.e.*, which is of the same brightness when viewed from all angles. The simple test plate supplied with standard photometers is as close an approximation to such a condition as it is practicable to provide. Nevertheless this test plate, like those of other photometers, introduces material error when employed in the measurement of light at grazing incidence. These errors are very material, amounting to as much as 40 per cent with light incident at 80 deg. to the normal (Fig. 6-3). Of course, no such errors are encountered in practical illumination measurements, since the component received at such acute angles is not large. Errors of 5 to 10 per cent, however, are frequently experienced as a result of the incorrect rendering of illumination intensities by ordinary test plates. Still greater errors are sometimes encountered in the measurement of street illumination intensities.

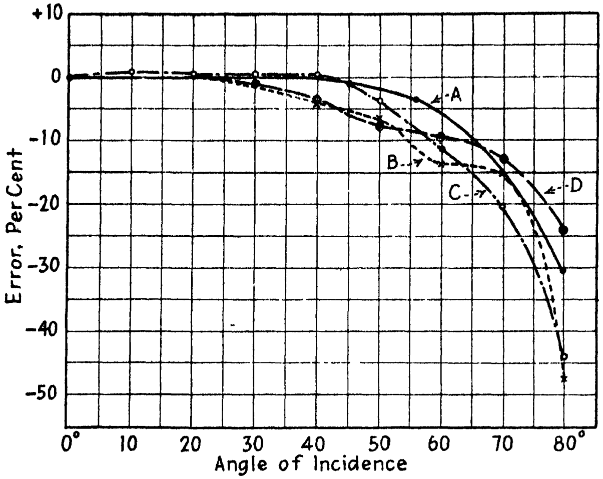

FIG. 6-3.—Test-plate errors. *A*, reflection from polished glass, $n = 1.5$, reduced to zero reflection at normal; *B*, errors of polished white-glass test plate; *C*, errors of polished white-glass test plate; and *D*, errors of depolished white-glass test plate.

If additional light could be introduced to the plate, so proportioned as to be zero at normal incidence and to increase rapidly from 50 deg. on, this deficiency might be overcome and the test plate caused to give correct results. It is this idea which underlies the compensated test plate. The construction is very simple. The transmitting test plate, instead of being mounted on the end of a metal tube, is mounted on a little ring of diffusing (opal) glass.

The brightness of the test plate with 0-deg. incidence is not altered by the presence of the opal ring except by internal reflections, but as the incidence increases a larger and larger amount of light falls upon the ring and, by it, is diffused in such a way as to add a certain illumination to the under surface of the test plate. By properly proportioning the transmission of the test plate and the transmission and diffusion of the ring, together with the width of the latter, a compensation for the deficiency in brightness of the test plate at high angles may be obtained.

It is evident that if the arrangement as described were used, light coming at 90 deg. of incidence, which would produce no illumination whatever on the upper side of the plate, would pass through the opal-glass ring and illuminate the under side of the plate. Light coming from angles even greater than 90 deg. might have the same effect. Evidently this light must be cut off, and this is done by the interposition of a saucer-shaped screen with

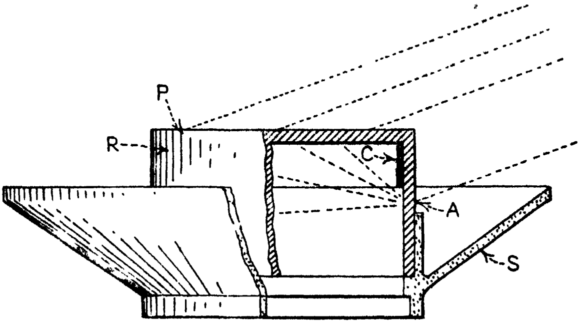

Fig. 6-4.—Compensated transmitting test plate. *P*, test plate of polished white glass; *R*, ring of opal glass; *C*, opaque shield; *A*, clear aperture in ring for admission of light; and *S*, screen to cut off light at 90-deg. incidence.

the edge of the saucer in line with the top of the aperture in the opal ring. The construction used is shown in half section in Fig. 6-4 and the actual test plate as attached to a photometer is shown in Fig. 6-6.

It has been found that if the light is admitted to the opal ring close to the test plate the compensating illumination is not uniformly distributed over the test plate, so that at high angles of incidence the intensity of the field is irregular. Therefore the aperture in the ring is placed well below the test plate. The portion of the opal ring through which light should not pass is covered up by a metal band *C*, the width of which determines the width of the aperture in the compensating ring, and hence the amount of compensating light.

Evidently the amount of compensating light has to be accurately proportioned to fit the peculiarities of the test plate. If the test plate is quite thin and transparent, a larger amount of compensating light is required than if it is relatively dense. The more perfect the diffusing qualities of the test plate the less compensating light is required.

The construction whereby reflecting test plates may be compensated in accordance with the above-mentioned principles is quite as simple as that of the transmitting test plate. The reflecting test plate proper is made of a disk of depolished white glass; parallel with this disk is placed another similar disk. A similar opaque screen is used for shielding the upper disk from light coming at angles of 90 deg. and greater. Compensation is affected by the light reflected from the lower disk which passes through the upper disk and adds a sufficient amount to the brightness of the test surface. This construction is shown in section in Fig. 6-5. Here, again, the results of the compensation, while not quite so good with the reflecting plate, are, for practical purposes, about as good as could be desired. It should be noted, however, that the reflecting plate suffers from the disadvantage that, in order to give these results, the angle of view must be normal to the plate. There does not seem to be any way of obviating this disadvantage. Also the reflecting plate is considerably more cumbersome than the transmitting plate on account of its dimensions. Evidently, the plate itself must be of sufficient size to cover the entire field of the photometer when the photometer is placed at the desired distance from it. The shading ring surrounding it must be large enough so that it does not begin to cast a shadow on the lower plate at too small an angle of incidence; otherwise the compensation at high angles of incidence will be incomplete. In the construction investigated the test plate had a diameter of 5 in. and the entire apparatus a diameter of 10 in.

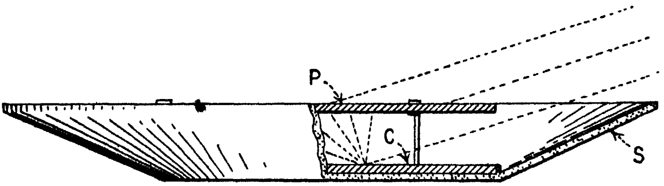

FIG. 6-5.—Half section of compensated reflecting test plate. *P*, test plate of depolished white glass; *C*, compensating diffuser of depolished white glass; and *S*, screen for cutting off light at 90 deg.

The transmitting compensated test plate is attached to the photometer as illustrated in Fig. 6-6. The reflecting compensated test plate is a separate device and may be located wherever desired, as, for example, in Fig. 6-7, where it is employed in the measurement of illumination just over the surface of the street.

The Photronic Cell Photometer.[1]—The discovery that selenium barrier-layer cells and copper oxide barrier-layer cells generated an electric current when exposed to light has led to their development and use with a microammeter as a portable physical photometer. The characteristics of the selenium barrier-layer cell are more desirable for this purpose. The Weston photronic foot-candle meters and the General Electric light meter are examples of this type of photometer.

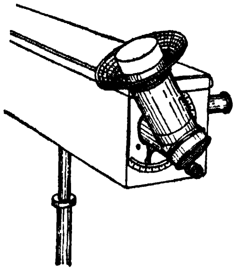

FIG. 6-6.—Use of compensating test plate shown in Fig. 6-4.

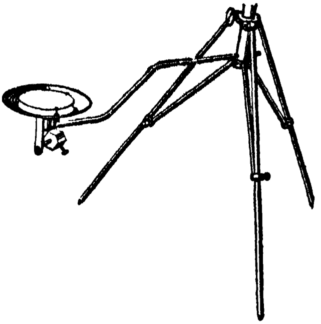

FIG. 6-7.—Use of compensating test plate shown in Fig. 6-5.

The cell consists essentially of a thin, metal disk on which there is a film of light-sensitive material. The metal disk forms the positive terminal and a metal collector ring in contact with the light-sensitive surface forms the negative terminal.

The cell is contained in a case having a window of glass or quartz depending upon whether the cell is to be used only in the visible or infrared regions of the spectrum, or in the ultraviolet.

The action of the light impinging upon the sensitive surface is entirely electronic, and all tests so far made indicate that no chemical or physical change takes place due to the radiant flux, so that the life of the cell seems to be unlimited, unless damaged in some way.

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[1] GOODWIN, *Trans. Illum. Eng. Soc.*, vol. 27, p. 828, 1932.
FOGLE, *ibid.*, vol. 31, p. 773, 1936.

The current output of the average cell is about 1.4 microamp. per foot-candle uniformly distributed over the sensitive surface, when connected to a relatively low external resistance. The area of the sensitive surface is about 1.8 sq. in. so that the output of the cell is about 120 microamp. per lumen.

The cell remains constant to a high degree of accuracy unless damaged, subjected to excessive temperatures (above 50°C.) or to moisture.

When radiant energy enters the eye it is automatically judged according to the visibility curve. The value assigned by the observer as to its absolute visibility value is unreliable. By means of the light-sensitive cell he may determine relative intensities with considerable precision if they are of the same chromaticity and with less precision if they are of different chromaticities.

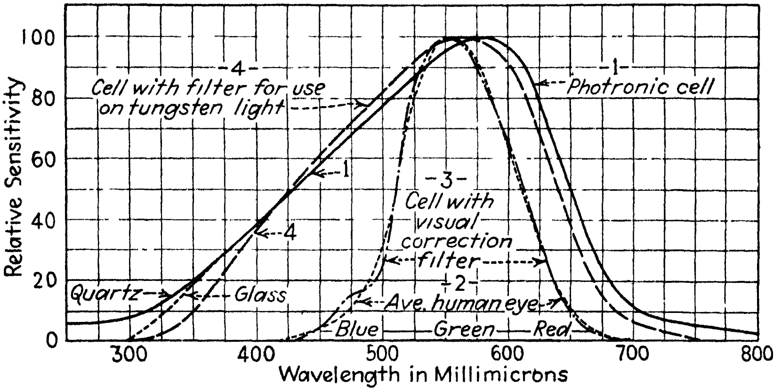

FIG. 6-8.—Photronic-cell sensitivity with and without filters.

The performance of the photronic cell is shown by curve 1, Fig. 6-8. The visibility curve of the eye is included for reference. The cell sensitivity is seen to cover a much wider range than eye sensitivity and certain radiations are effective on the cell that are not visible to the eye. Also those radiations effective to both the cell and eye are not equally effective to both. The result is that the cell and the eye do not evaluate equally lights differing in spectral composition. For sources of light having a continuous spectrum proper results comparable with the eye can be obtained by multiplying the cell output by the proper factor for that light.

If the spectral response of a cell differs widely from the standard visibility curve the cell should not be used to measure the luminous values of lights differing considerably in spectral selectivity. On the other hand, there are many measurement applications for which the photoelectric cells are eminently suitable and where their speed and precision render them greatly superior to the eye. For the measurement of the distribution of intensity about a lamp or lighting fixture or the reflection at different angles from a surface, where the spectral quality of the light is the same throughout, and for illumination surveys or intensities of illumination in different parts of a room under constant conditions, this type of cell is eminently suitable.

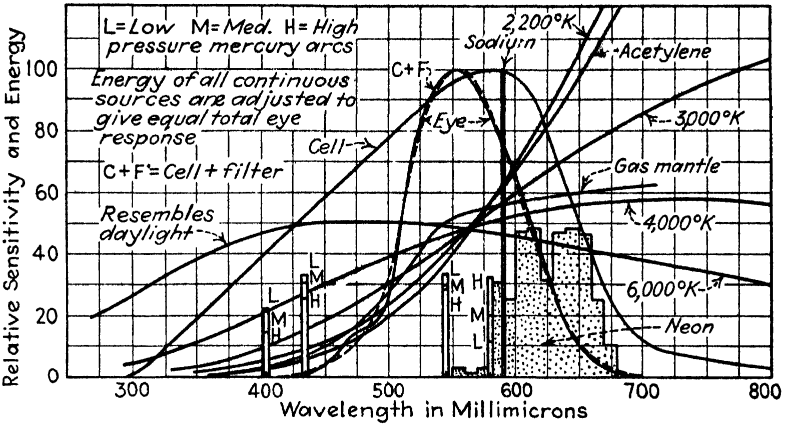

FIG. 6-9.—Photronic-cell and energy-radiation curves.

Obviously in work of a photometric nature it is best to use a cell the response of which does not deviate too widely from the visibility curve, in order that unsuspected deviations in spectral quality, even though small, may introduce no important error.

Filters have been developed to correct the response of the cell to various degrees as may be desired. Curve 4, Fig. 6-8, shows the response with a filter for use on tungsten lamps.

A visual-correction filter for use on the photronic cell consists of a yellow glass which removes the excess blue and a blue glass which removes the excess red response. The result is shown by curve 3 in Fig. 6-8 or curve $C + F$ in Fig. 6-9 which are closely similar to the visibility curve of the eye.

With a cell and filter combination having an effective sensibility identical with that of the average eye, the spectral composition of the light is immaterial because the sum total response to all the different wave lengths will be the same for cell plus filter as for the average eye. This may be appreciated by a study of the spectra indicated in Fig. 6-9.

One model of the Weston photronic cell is shown in Fig. 6-10. Its use is obvious. The cell is placed where the illumination is to be measured and the value of the intensity in foot-candles read off the scale of the microammeter.

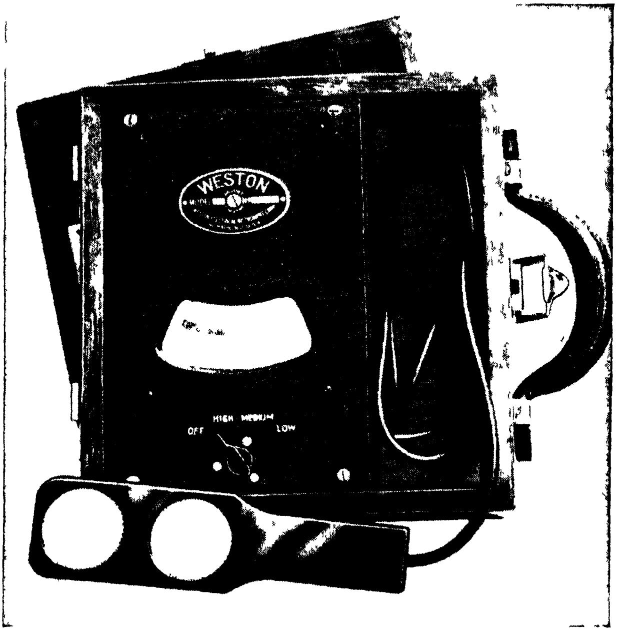

FIG. 6-10.—The photronic foot-candle meter.

Measurement of Coefficient of Reflection.—There are a number of laboratory methods of obtaining this value, some of which employ elaborate apparatus and take into account with a high degree of accuracy the direction of the incident light, color of incident light, and similar features.

The practical determination of the coefficient of reflection of a diffuse-reflecting wall or ceiling is quite simple and can be made by anyone familiar with the operation of a portable photometer employing a detached test plate. The standard on which reflection factors are based is a freshly scraped block of pure magnesium carbonate. One of these standards may be secured at any drug store; a block approximately 4 in. square and 2 in. thick may be purchased for a few cents. The first step in the determination is to scrape the surface of the block and place it in any convenient position relative to an artificial light source. The photometer is then pointed at the block from some angle not far from the normal and a reading taken and recorded. A secondary standard, or working standard, such as a sheet of blotting paper, is next calibrated. This is substituted for the magnesium block, and with the same illumination incident on it as when the previous reading was taken, a second reading is taken and recorded. The following proportion is then applied: Reading A is to 98 per cent as reading B is to the coefficient of reflection of the blotting paper.

Taking care that the blotting paper, or secondary standard, does not become dirty, it is removed to the room in which the test is desired, placed at a convenient position on the wall or ceiling the reflection factor of which is desired, and with the portable photometer a reading is taken of the brightness of the blotting paper with the normal illumination received on the wall incident on the paper. The paper is now removed and a reading taken of the wall surface. The coefficient of reflection of the blotting paper has already been determined and the following proportion applies: Reading on blotting paper is to the coefficient of reflection of blotting paper as reading on wall is to the coefficient of reflection of wall.

If the surface to be tested is polished or has a considerable element of specular reflection, then the determination of the coefficient is more complex, and several readings at different angles should be taken to ensure obtaining fair average value.

Illumination Surveys.—Illumination surveys, or measurements of illumination at points on a reference plane, are frequently made to determine the intensity and distribution of the illumination from a lighting installation. This method is often employed to compare the lighting efficiency of two classes of lighting apparatus. In this latter case too much weight should not be given results so obtained since, due to absence of glare and to greater diffusion of the light, the system giving the lower average foot-candle intensity may be more effective and more satisfactory.

Foot-candle measurements of illumination are ordinarily taken by placing the test plate of the instruments in a horizontal position at the desired place. For general illumination in mills and factories, readings are made at an imaginary plane 3 ft. above the floor, while in offices the plane of the desk tops, 30 in. above the floor, is used.

For special cases such as the lighting of shelving, storage bins, or pictures in art galleries, the foot-candles on a vertical plane are the values which interest the careful investigator. In a railway coach or library, the illumination on a 45-deg. plane—that in which reading matter is ordinarily held—is the value taken.

All records of illumination tests are much more valuable and comparable if the conditions of the test and the data concerning the surroundings are recorded. Records of mere foot-candle readings, without reference to such influencing factors as voltage, cleanliness of lighting devices, color of interior, etc., tell but half the story.

In making tests of this nature it is customary to divide the test area into a number of small equal sections and to measure the intensity of the illumination at the center of each section. If the room is very large and the lighting units are well distributed it is often sufficient to measure the illumination in a number of equal sections of a part of the total area. Assuming that the result of each measurement represents the average intensity of that section, it follows that the average illumination will be the average of these readings. The total light flux in lumens will equal the average intensity in foot-candles multiplied by the area in square feet.

The method of laying off a room into sections for a test as explained above is illustrated in Fig. 6-11. The 15 lamps are located at 1, 2, 3, etc., as shown. It will be seen that the four quarters of the room are similar; consequently, one-fourth of the room may be divided into sections and readings taken at *a*, *b*, *c*, *d*, etc., to obtain the average intensity for the room.

It often happens when all the light is received from one lamp, or cluster, and where the class of service makes it impossible to measure the illumination at the proper places that a certain direction from beneath the source may be chosen, along which the illumination may be measured, and the average intensity calculated from these readings. The locations of test stations for a survey of this nature are shown in Fig. 6-12 by the points *a*, *b*, *c*, *d*, etc. It is essential in a test of this nature that the distribution of light from the source be equal in azimuth and that the reflected light be proportionately distributed; in other words, the measurement at each station should represent the average intensity along the circumference of a circle drawn through that station with the point beneath the source as a center. The representation, interpretation, and calculation of the measurements thus obtained are given on the following pages.

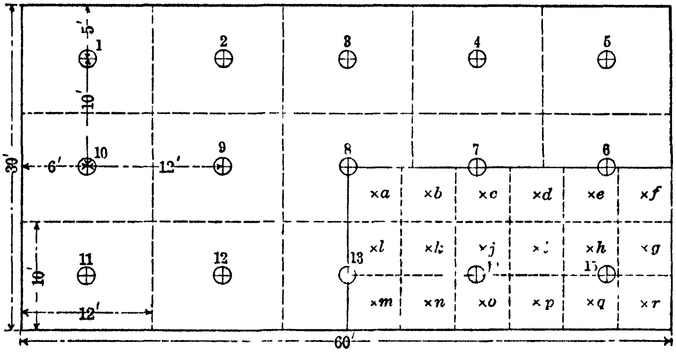

FIG. 6-11.—Location of test stations for illumination survey.

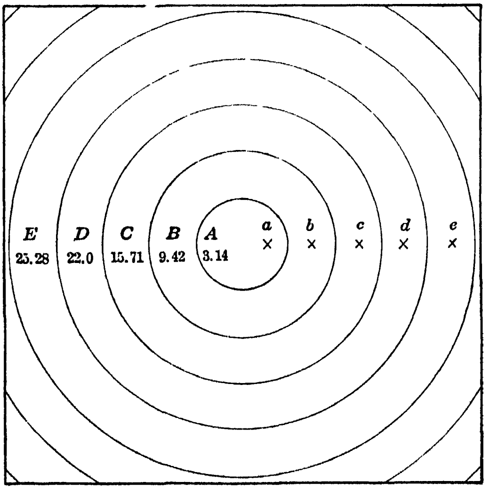

FIG. 6-12.—Areas and test stations for circular equiluminous areas.

Representation of Results.—The results of calculations of illumination intensity by the point-by-point method and the values obtained by illuminometry may be presented as numerical values in tabulated form, or they may be represented graphically by curves showing the intensity at different distances from beneath the source, or by "equiluminous lines" showing the regions of equal intensity with the value of the intensity given on each line. Still more elaborate methods combining the two just mentioned and showing one or both in perspective or by projection may be employed.

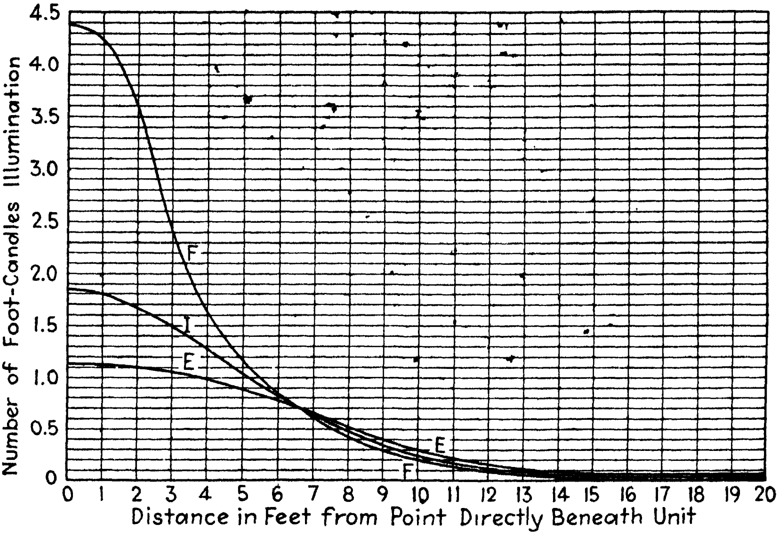

FIG. 6-13.—Curves showing illumination produced by a lamp with extensive, intensive, and focusing types of reflectors.

With one lamp the values of illumination intensity may be represented as shown by Fig. 6-13. These curves represent the distribution of illumination from a 100-watt tungsten lamp when equipped with extensive, intensive, and focusing types of high-efficiency reflectors and when placed 8 ft. above the illuminated plane.

In the same way that the polar curves showing the distribution of light from a source may lead to erroneous impressions regarding the light flux emitted, the illumination diagram of foot-candle values at various distances may also be misinterpreted in regard to the amount of light flux. It should be remembered that these curves represent the intensity at different distances from a point beneath the lamp and that the intensity along a circle with this point as a center and a radius of, say, 4 ft. will be the same as shown at 4 ft. by the curve. If the illuminated area is assumed to be laid off into a number of concentric circular surfaces, centering beneath the source (Fig. 6-12), it will be readily understood that while the intensity may be less at a distance from beneath the source it is illuminating a greater area and the total light flux may be more than in smaller areas when the intensity is much greater. If such areas are designated by A, B, C, D, etc., each 1 ft. in width, then the areas are

$$\begin{aligned}
A &= \pi 1^2 &&= \pi &&= 3.14\\
B &= \pi(2^2 - 1^2) &&= 3\pi &&= 9.42\\
C &= \pi(3^2 - 2^2) &&= 5\pi &&= 15.71\\
D &= \pi(4^2 - 3^2) &&= 7\pi &&= 22.00\\
\hline
&& \text{Total area} &&&= 50.27 \text{ sq. ft.}
\end{aligned}$$

and if the average illumination intensity of A, B, C, and D be 4, 3, 2, and 1 foot-candles, respectively, then the total flux in lumens is

$$\begin{aligned}
A &= 3.14 \times 4 = 12.56\\
B &= 9.42 \times 3 = 28.26\\
C &= 15.71 \times 2 = 31.42\\
D &= 22. \quad \times 1 = 22.\\
\hline
&\text{Total flux} = 94.24 \text{ lumens}
\end{aligned}$$

Hence the average illumination will be

$$\frac{94.24}{50.27} = 1.87 \text{ foot-candles or lumens per square foot}$$

and not

$$\frac{4 + 3 + 2 + 1}{4} = 2.5 \text{ foot-candles}$$

The distribution of illumination from two or more lamps may be represented as shown in Fig. 6-14. These curves show the intensities along a line connecting points beneath the sources when the lamps are equipped with intensive, extensive, and focusing types of reflectors. In this case the lamps are placed 14 ft. apart and 12 ft. above the illuminated plane.

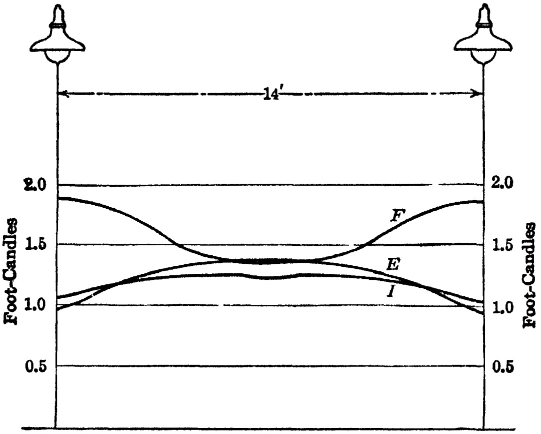

FIG 6-14 —Showing illumination due to two units with three types of reflectors. (Lamps spaced 14 ft apart and 12 ft above the floor)

From a study of these curves it will be seen that more uniform illumination can be obtained by changing the ratio of the distance

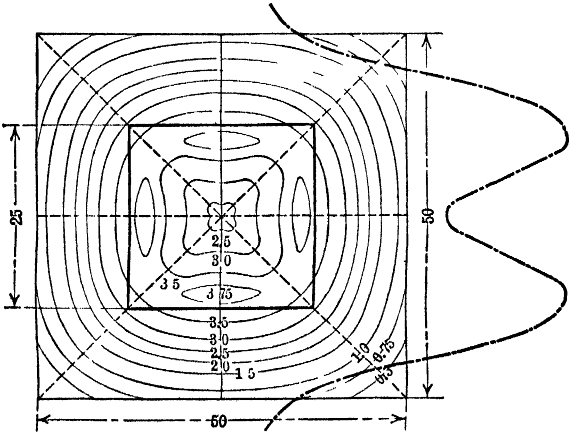

FIG. 6-15 —Representation of illumination values.

between the sources to the height of suspension. With the focusing equipment the ratio d/h must be decreased, *i.e.*, the distance between lamps must be decreased or the height of suspension increased. At the same time it is obvious that the intensity of illumination will change, increasing as the lamps are brought nearer and decreasing as they are elevated. By similar reasoning the other two types must be placed farther apart or lower, and the extensive type more than the intensive type.

A satisfactory method of representing the intensity of illumination over certain areas is to lay off the illuminated surface to some convenient scale and calculate and plot equiluminous lines. Such a diagram is shown in Fig. 6-15, which illustrates the distribution of illumination from four sources of rather strong downward intensity placed over the areas receiving the greatest illumination. The vertical distribution of light through the center of the surface is represented by the broken line at the side of the diagram.

Determination of the Mean Horizontal Intensity of a Source of Light.—There are at the present time several methods for the determination of the so-called mean horizontal intensity of incandescent lamps, *i.e.*, the mean intensity in the plane perpendicular to the axis of the lamp and passing through its center. The oldest of these methods, and one which is equally applicable to other light sources, consists in measuring the intensity at equal angular intervals in the horizontal plane and either taking the mean of these observed values or plotting the observations and determining the mean radius vector of the curve drawn through the plotted points.

A second method is an abbreviation of the first. Photometric measurements are made in a single fixed direction and the mean horizontal intensity is computed from mean horizontal reduction factors previously determined for each type of lamp. This method is not recommended where accurate results are desired, because of the difference in lamps having the same type of filament. This difference occurs partly in the shape of the filament and partly in the nonuniformity of the glass globe.

A third method, and one which is extensively used in this country in the practical determinations of the mean horizontal intensity of incandescent lamps, consists in revolving the lamp about its axis at a uniform speed. For this purpose a device has been designed having a revolvable socket to which electrical connections are made by means of brushes and collector rings. The socket is supported by an arrangement whereby readings can be taken not only in the horizontal plane but in other directions in a vertical plane through the axis of the lamp with the lamp revolving about its axis. In this way the mean intensity in different directions in a vertical plane may be determined. This method possesses two possible sources of error: (1) distortions of the filament due to centrifugal force; (2) flicker, which is perceptible in nearly all types of lamps when rotating. Investigations have shown, however, that at 180 r.p.m. changes in intensity due to centrifugal action lie within the range of experimental error. But with most types of lamps the speed cannot be raised until flicker disappears without introducing error due to distortion of the filament. The principal source of error[1] appears to be flicker and this error differs with different individuals. The conclusion drawn from the investigations cited above is that, where the horizontal distribution curve deviates considerably from a circle so that a bad flicker results when the lamp rotates at 180 r.p.m., some other method for determining the mean horizontal intensity should be employed.

A fourth method of obtaining the mean horizontal intensity of a lamp consists in rotating a pair of mirrors about the lamp, which is held in a stationary position. The lamp is mounted with its axis horizontal and coincident with the photometric axis, the tip of the lamp being turned toward the photometer screen. The two mirrors, inclined at approximately 90 deg. to each other, reflect to the photometer screen light emitted from the lamp in a direction perpendicular to its axis. The direct rays from the lamp are prevented from reaching the photometer by a small screen. The mirrors rotate about the axis of the lamp and reflect to the screen a quantity of light proportional to the mean horizontal intensity of the source. This method necessitates, of course, the determination of the reflection coefficients of the mirrors, which is accomplished by means of a standard lamp, the mean horizontal intensity of which has been previously determined by the first method mentioned above.

The arrangement of the rotating-mirror apparatus is shown in Fig. 6-16. For experimental purposes it was so constructed that the lamp could be rotated independently of the mirrors. The mirrors may be rotated by a motor belted to pulley *E*. The mirrors are held to the frame by the bolts *B* and the frame prevented from spreading by the stay rods *C*. The screen *D* intercepts the direct rays from the lamp.

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[1] *Bur. Standards Bull.*, vol. 2, p. 426, 1906.

It was found that gas-filled lamps, when rotated for the purpose of determining their mean horizontal candle power, changed both in current consumption and in candle power, and that this change varied with the speed of rotation. This change was attributed to the centrifugal force, which caused the cooler portions of the gas in the interior of the bulb to be thrown off to the periphery of the bulb, leaving the filament surrounded by hotter gas than if it were stationary. Hence the temperature of the filament increased, and with it the candle power and the efficiency of the lamp. It was found further that at low speeds of rotation the candle power of these lamps decreased, so that for every lamp a speed can be found at which the candle power and the watts are the same as when stationary. It was found that the determination of the mean horizontal candle power of gas-filled lamps could be accomplished by rotating the lamp quite

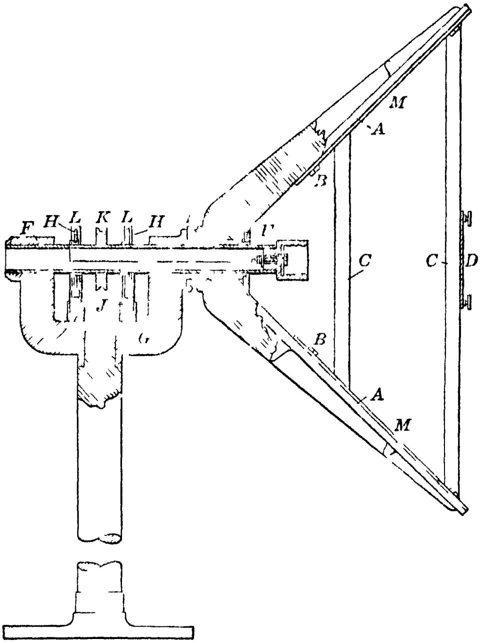

Fig. 6-16 Rotating mirrors

slowly at or near this critical speed and placing behind it two mirrors 120 deg. apart, so that the photometer disk is illuminated not only by the lamp itself but by its two reflected images resulting from beams equally directed about the periphery of the lamp. The two mirrors are employed to obviate the violent flicker on the photometer disk which would otherwise occur.[1]

Apparatus for Obtaining Values for the Polar Curve.—In determining the distribution of light around a lamp which must be burned in a certain position, which cannot be inclined without introducing variations in its candle-power values, it becomes necessary to resort to other means than those heretofore described.

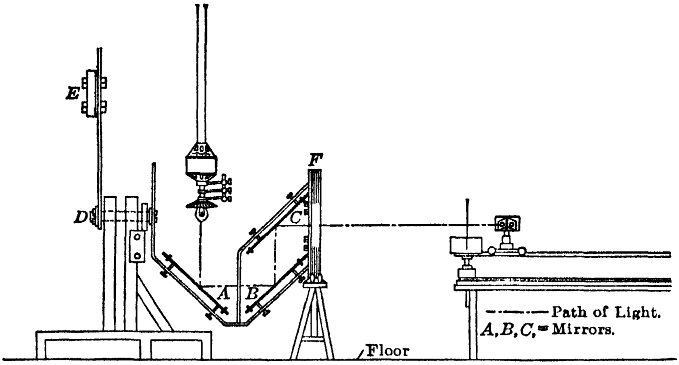

Fig. 6-17.—Mirror-reflector photometer.

For this purpose *a device consisting of three mirrors A, B,* and *C* revolvable about an axis *D* is shown in Fig. 6-17. It will be seen that the beam of light follows a path indicated by the broken line and is compared on the photometric device shown in the right-hand side of the figure. It will be seen that the mirrors can be rotated so as to measure the candle power in a vertical plane. It is obvious that this device can be used for photometering any ordinary source of light and can be calibrated by substituting a source of known candle power in the same way as with the portable photometers.

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[1] *Trans. Illum. Eng. Soc.*, vol. 9, p. 1020, 1914; *Bur. Standards Bull.*, vol. 12, p. 589, 1916.

Another arrangement is shown in Fig. 6-18.[1] This method embodies many desirable features and deserves more than passing notice. It will be seen that the direct rays from the lamp are intercepted by a black screen placed in the photometric axis. The light which is measured is reflected by the mirrors and strikes the photometer screen at an acute angle. This necessitates *calibrating the apparatus,* which may be accomplished either by placing a source of known candle power in the same place as the test lamp, or by removing the intercepting screen and the mirrors and obtaining the constant of the apparatus by comparing the horizontal intensity obtained in this way with the readings obtained when the mirrors were in the horizontal plane and the screen in position. It is obvious that the mirrors are placed as shown merely to illustrate the construction, and when in actual operation each is similarly placed on opposite sides of a vertical line passing through the center of the source of light. Thus if it be desired to determine the candle power 15 deg. below the horizontal a mirror should be placed on opposite sides of the lamp 15 deg. below the horizontal.

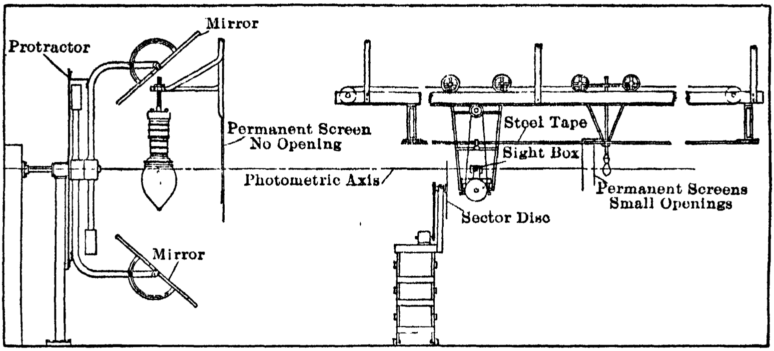

FIG. 6-18.—Arrangement of twin-mirror photometer.

Obviously one mirror can be used instead of two, but two mirrors offer an advantage in reducing the fluctuations in intensity due to irregularities in the glass or location of the light source.

It will be seen from the figure that a *rotating sector disk* driven by a small motor is placed in the photometric axis. This is used to increase the range of the apparatus by decreasing the intensity on that side of the photometric sight box. The sight box and the standard lamp are suspended from a track located above the photometric axis. Reflected light due to the standard lamp is intercepted by opaque screens placed between the standard lamp and the sight box and having openings along the photometric axis large enough to let the direct rays pass through. A photometrical balance may be obtained by changing the size of the openings in the rotating sector disk and varying the distance between the standard lamp and the sight box. The sight box should remain in the same position as when the apparatus is calibrated, so that the incident angle of the light rays will be the same. For very low intensities or with a high candle-power standard the sector disk may be placed on the other side of the sight box. In this way the range of the apparatus may be varied to meet almost any value of intensity.

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[1] *Trans. Illum. Eng. Soc.*, vol. 6, p. 641, 1911.

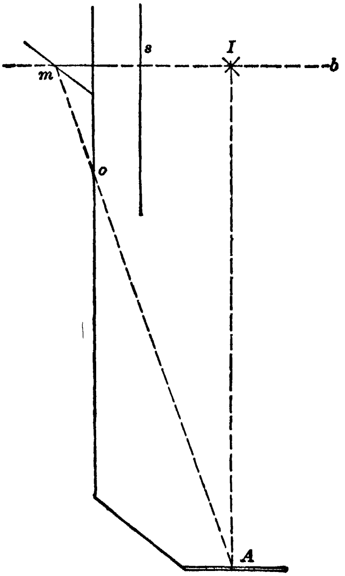

FIG. 6-19.—Revolvable test plate for determining the distribution of light.

Another arrangement for the same purpose, but simpler in construction, is illustrated graphically by Fig. 6-19. Assume the source to be located at *I* and a *test plate A revolvable about the photometrical axis mb* to receive the illumination to be measured. The illumination on the test plate *A* may be viewed through a photometric device placed on the photometric axis and the mirror *m* located so as to rotate with the test plate. Since the illumination varies inversely as the square of the distance, the candle power can be calculated from the illumination measurements, or the device may be calibrated to read the candle-power values directly, in the same way as in the case just described. It is evident that a mirror must be substituted for the screen in the photometric device on the side receiving the light from the test plate. The test plate must, obviously, be far enough from the source so that the source may be considered a point source, since the reflection from the test plate will differ from that from a mirror.

Still another apparatus for the same purpose, but even simpler in construction and operation, is to place a light-sensitive cell at *A* in place of the test plate and eliminate the photometric apparatus. Then by means of a microammeter connected to the cell and properly calibrated, the candle-power values can be read directly for the various positions as the cell is revolved around the lamp. A single cell so mounted is shown in Fig. 7-24 in the next chapter.

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CHAPTER VII

LIGHT-FLUX CALCULATIONS AND SPHERICAL PHOTOMETRY

LIGHT-FLUX CALCULATIONS

In order to compare luminous sources on the basis of the total amount of light emitted and to be able to determine the amount of light available for illuminating purposes it becomes necessary to understand some of the methods used and the underlying principles involved in obtaining the *total amount of light flux emitted,* or any part thereof, by any lighting equipment.

The various methods used in practice for determining the value of the candle power in different directions from the source have been described in the preceding chapter. These values are usually represented graphically by curves plotted to polar coordinates. These curves merely show the distribution of light in one plane (usually the vertical plane) around the source of light as a center. They simply indicate the value of the candle power in definite directions from the source and have no significance as a representation of the quantity of light.

Polar Curves and Spherical Surfaces.—An interesting comparison indicating the misleading conceptions likely to arise in the study of polar diagrams is illustrated by the polar curves of Fig. 7-1. The four curves *a, b, c,* and *d* represent theoretical distributions of light in a vertical plane. The maximum values in these four cases are approximately in the ratios of 15:19:50:60. However, if these curves represented the distribution of light from luminous sources in a vertical plane, the mean spherical candle power or the *total flux of light would be the same for each.*

To understand the reason for this it is necessary to realize the difference in the area of the imaginary zones through which the light represented by these candle-power values passes. In quadrant *A* of Fig. 7-2 are shown half of such zones subtended by 10-deg. angles. It will be seen that the 80–90 deg. zone is a large band circling the sphere while the 0–10-deg. zone is a small disk at the bottom. The areas are in the ratio of 11.44:1. Thus if the candle power were the same in the direction of each of these zones the light or lumens received by them or passing through them would be in the ratio of 11.44:1. If now this spherical surface be divided into 10 zones of equal areas, as shown in quadrant *B*, the angle subtending the first zone below the horizontal (90-deg. line) will be 5.7 deg. (90 − 84.3), while the angle subtending the bottom zone is 25.8 deg. Since these 10 zones are of equal areas, if the average candle power for each zone is known the mean hemispherical candle power will be the

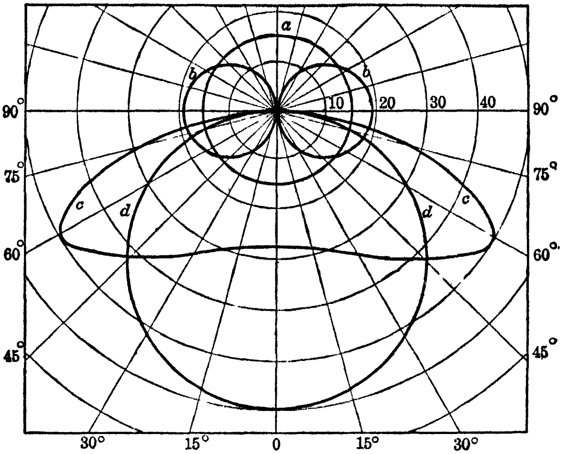

Fig. 7-1.—Polar curves giving the same amount of light.

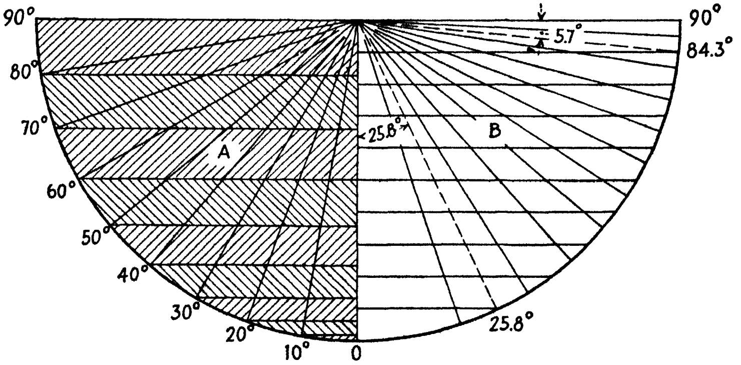

Fig. 7-2.—*A*, zones subtended by equal (10-deg.) angles; *B*, zones (10) of equal areas. Ten radial lines represent central points of the equal zones.

sum of the 10 average values divided by 10. The 10 radial lines represent the central points of these zones of equal area, therefore the average of the candle-power values along these 10 lines will be the mean lower hemispherical candle power.

The fundamental theory of this section of the subject is based on the study of spherical surfaces, in junction with which it becomes necessary to determine either the mean spherical intensity in candle power or the zonal or total flux of light in lumens. In these spherical calculations it is assumed that the luminous intensity is equal in azimuth and varies only in one plane through the source which, in the following discussion, will be a vertical plane.

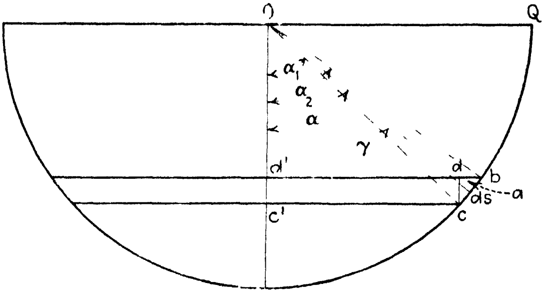

FIG. 7-3.—Area of a zone is proportional to its altitude.

If the source of light is assumed to be surrounded by a sphere of radius r with the source as a center and, further, this sphere is considered to be divided into a number of zones in such a manner that the illumination of similar parts of each zone is uniform, the total flux of light embraced by a zone will be equal to the product of the average intensity and the area of the zone. From a summation of these products for each zone the total value of light flux emitted by the source may be obtained and this divided by 4π will give the mean spherical candle power. The light flux in the hemisphere will be the sum of the products of the areas of the zones of the hemisphere and their respective intensities, and this sum divided by 2π will give the mean hemispherical candle power.

The mathematical deduction for the foregoing relations is as follows: With the light source at the center of a sphere of radius r (Fig. 7-3) the width of the zone subtended by the angle da at an angle a from the vertical is rda. This zone forms a band around the sphere and has a radius of $r \sin a$ and a length of $2\pi r \sin a$. Its area will be

$$2\pi r^2 \sin a \, da \tag{7-1}$$

Since E (the illumination) equals I_a/r^2, the light flux is

$$F_a = 2\pi I_a \sin a \, da \tag{7-2}$$

By integrating from 0 to $\pi/2$ the total luminous flux for the lower hemispherical area will be

$$F_{hs} = 2\pi \int_0^{\frac{\pi}{2}} I_a \sin a \, da \tag{7-3}$$

or the total flux for the spherical area will be

$$F_s = 2\pi \int_0^{\pi} I_a \sin a \, da \tag{7-4}$$

If the candle power is uniform in all directions the above equation becomes

$$F_s = 4\pi I_{ms} \qquad \text{and transposed} \qquad I_{ms} = \frac{F_s}{4\pi} \tag{7-5}$$

The zone subtended by the angle da has the width $ds = bc$ and the area equal to this width times the circumference of a mean circle through ds. The periphery of this circle is equal to the periphery of a circle through Q times $\sin a$, and

$$ds = rda = bc = \frac{dc}{\sin a}.$$

The area of a zone for a sphere of unit radius

$$= 2\pi \sin a \times cb \tag{7-6}$$

$$= 2\pi \sin a \times \frac{dc}{\sin a} \tag{7-7}$$

$$= 2\pi \times dc \tag{7-8}$$

and the light flux in the zone ds is

$$F = 2\pi I_a \times dc \tag{7-9}$$

where dc = the altitude of the zone ds.

It will be seen from Fig. 7-3 that dc is equal to $\cos a_1 - \cos a_2$. Thus the luminous flux in any zone of an imaginary sphere surrounding a source of light is

$$F_{ds} = 2\pi I_a(\cos a_1 - \cos a_2) \qquad (7\text{-}10)$$

where $a_1 - a_2$ is the angle subtending the zone of reference, a_1 and a_2 being angles measured from the vertical, and I is the average intensity of candle power in the zone.

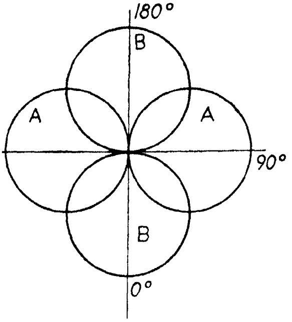

FIG. 7-4.—Polar curves having same maximum values but light flux in the ratio of 3:2.

In the case of polar candle-power curves, as shown by curves A and B in Fig. 7-4, the value of the light flux may be derived as follows:

When the candle power I_m is a maximum in the horizontal or 90-deg. direction

$$I_a = I_m \sin a$$

Then from equation

$$\begin{aligned} F_A &= 2\pi I_m \int_0^\pi \sin^2 a\, da \\ &= 2\pi I_m \left[\frac{a}{2} - \frac{1}{4}\sin 2a\right]_0^\pi \\ &= \pi^2 I_m = 9.86 I_m \end{aligned}$$

When the candle-power distribution is as indicated in Fig. 7-4B

$$I_a = I_m \cos a$$

and substituting as above

$$\begin{aligned} F_B &= 2\pi I_m \int_0^\pi \cos a \sin a\, da \\ &= 2\pi I_m \Big[\sin^2 a\Big]_0^{\frac{\pi}{2}} \\ &= 2\pi I_m = 6.28 I_m \end{aligned}$$

There are several methods of determining the light flux in the various zones and determining the mean candle-power values.

One method is to derive the values of $2\pi(\cos a_1 - \cos a_2)$ for the different zones as indicated above. Then these values multiplied by the average candle power in the respective zones indicate the lumens in those zones. The sum of the lumens in the zones of the lower hemisphere divided by 2π is the mean lower hemispherical candle power. The sum of the lumens in the zones of both hemispheres divided by 4π will give the mean spherical candle power. A set of lumen constants for 10-deg. zones are given in Table 7-1. Thus if the candle power in the 85-deg. direction is 100, the lumens in the zone extending 10 deg. below the horizontal will be approximately

$$100 \times 1.0911 = 109.11 \text{ lumens.}$$

TABLE 7-1.—CONSTANTS FOR COMPUTING LUMINOUS FLUX FROM CANDLE-POWER CURVES

Mid-zone angle, degrees from vertical axis	Mid-zone angle, degrees from vertical axis	Zonal flux constants, 10-deg. zones
5	175	0.0954
15	165	0.2835
25	155	0.4629
35	145	0.6282
45	135	0.7744
55	125	0.8972
65	115	0.9926
75	105	1.0579
85	95	1.0911

The Rousseau Diagram.—The Rousseau diagram is the oldest of the various methods by means of which the mean spherical or hemispherical candle power and the luminous flux as a whole or in part may be obtained. In its construction advantage is taken of the proportionality of the areas of the zones of a sphere to their respective altitudes. The values of the altitudes of zones subtended by equal angles are laid off to scale along the vertical axis of the diagram. These may be determined graphically, as shown in Fig. 7-5, where the sphere is divided into 15-deg. zones and the zonal boundaries projected on the vertical.

If on the horizontal lines drawn from the terminals of the successive altitudes the values of the candle power in the direction of the corresponding angles are laid off to scale, then the area enclosed by the curve, determined by these values of the candle power at various angles, and the vertical, will represent the total luminous value of the source of light, and the proportional part of the total light in any zone will be clearly shown. The value

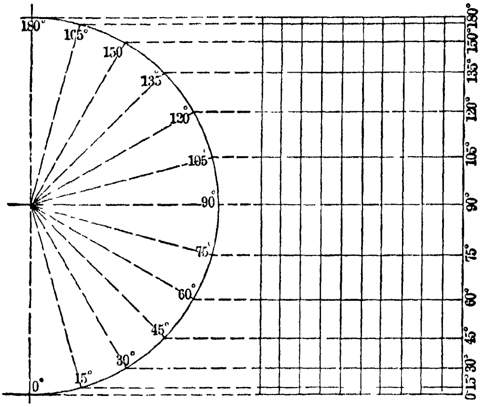

Fig. 7-5.—Construction of Rousseau diagram.

of this area in terms of the product of the scales to which the curve was plotted divided by the sum of the ordinates or altitudes will give the mean spherical candle power, and this value multiplied by 4π will give the flux in lumens. In the same way, areas corresponding to any zone or zones divided by the altitude or altitudes corresponding to the area will give the mean candle power throughout the respective portion of the spherical area. To obtain the value of the mean spherical or mean hemispherical candle power without a planimeter, the area enclosed by the curve may be divided horizontally by 20 lines bisecting areas of equal heights. Without appreciable error the average width of each section is assumed equal to the distance across the middle of that section. Hence by reading the lengths of these horizontal

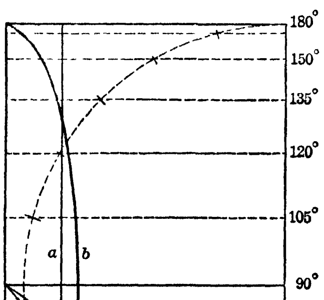

Fig. 7-6.—The Rousseau diagram applied to curves of Fig. 7-1.

lines and by dividing the sum of their values by 20 the approximate value of the mean spherical candle power is obtained. If the hemispherical candle power is desired, consider only the areas corresponding to that hemisphere and divide the sum of the values of the 10 lines by 10.

The use of the Rousseau diagram for showing the relative light values of different sources is shown in Fig. 7-6. The areas enclosed between the curves *a*, *b*, *c*, and *d* and the vertical on the left represent the total flux of light from four sources having distribution curves as indicated by *a*, *b*, *c*, and *d*, respectively, of Fig. 7-1. It will be seen that the four areas determined by the curves *a*, *b*, *c*, and *d* are equal. Since these areas represent graphically to scale the value of the light flux, the result is the same value of the lumens or mean spherical candle power for each.

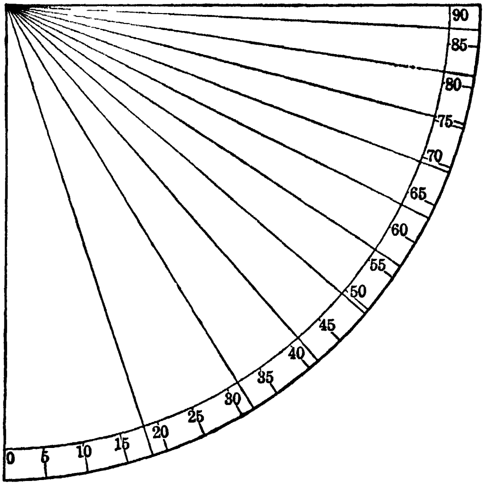

Fig. 7-7.—Device for obtaining mean hemispherical candle power.

In the method of determining mean spherical intensities just discussed it will be seen that the spherical area surrounding the source of light was divided into zones of equal areas and the candle power in the direction of the zonal centers of these areas assumed as the average for that zone.

A convenient method of applying this method to any polar candle-power curve is to draw the radial lines on transparent celluloid, as in Fig. 7-7, of convenient size to be placed over the polar curves. The values along these lines can be read and the average determined as before.

Wohlauer's Method.[1]—A method devised by Wohlauer offers a convenient means of determining the luminous flux and spherical candle power. The value of the flux is obtained by simply adding a number of linear dimensions drawn to scale and multiplying the same by some constant. This constant depends for its value upon the number of angular subdivisions of the spherical area.

It has been shown that the altitude and hence the area of a zone are proportional to the sine of the angle, measured from the vertical axis, which bisects the zone. Hence if the imaginary spherical area be divided into n numbers of equiangular zones, and assuming the mid-zone intensity to be the average for the zone, then the flux in any zone will be

$$F = kI \sin a, \tag{7-11}$$

where I is the average intensity of the zone, a the bisecting angle measured from the vertical axis, and k a constant the value of which depends upon the number of zonal subdivisions.

Referring to Fig. 7-8 and representing the flux in successive zones from the nadir by F_1, F_2, etc., the average intensities by I_1, I_2, etc., and the mid-zone angles by a_1, a_2, etc., then

$$F_1 = kI_1 \sin a_1 = kl_{ab}, \tag{7-12}$$
$$F_2 = kI_2 \sin a_2 = kl_{cd}, \tag{7-13}$$
$$F_3 = kI_3 \sin a_3 = kl_{ef}, \tag{7-14}$$

or

$$F = F_1 + F_2 + \cdots F_n = k(l_{ab} + l_{cd} + l_{ef} + \cdots) \tag{7-15}$$

where l_{ab}, l_{cd}, etc. are the horizontal projections of I_1, I_2, etc. Thus the flux in any zone is equal to the horizontal projection of its mid-zone intensity multiplied by the constant and the total flux in lumens is equal to the sum of the several projections multiplied by the constant.

The mean hemispherical candle power may be obtained by dividing the value of the flux in that hemisphere by 2π, and the mean spherical candle power may be determined by dividing the value of the total flux by 4π. The values of k for various angular subdivisions are given in Table 7-2.

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[1] *Illum. Eng.*, vol. 3, p. 655; vol. 4, pp. 148, 491; vol. 5, p. 132, 1910.

TABLE 7-2.—CONSTANTS FOR LIGHT-FLUX CALCULATIONS

Angular embrace of zone....	5°	10°	15°	20°	25°	30°
Value of *k*................	0.548	1.098	1.64	2.18	2.72	3.25

In the example just cited *k* is equal to 1.64, *a* being equal to 15 deg.

The polar diagram is constructed with vertical lines spaced equal to the polar scale to facilitate the evaluation of the projections of the various mid-zone intensities.

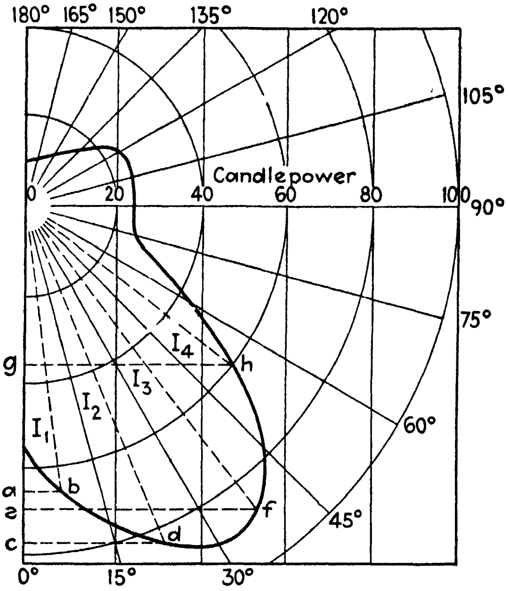

FIG. 7-8.—Wohlauer's method.

By referring to the values of the constants given above it is seen that for zones subtended by 10-deg. angles the value of *k* is 1.098. If now the polar curve (Fig. 7-8) is plotted on polar coordinate paper so dimensioned that 1.098 in. equals some multiple of the candle power, then the lumens can be determined directly by measuring the distances *ab*, *cd*, *ef*, etc. in inches and multiplying by the value of the multiple referred to above.

Modification of Wohlauer's Method.[1]—Still another application of the constant 1.098 conceived by the author is indicated by Fig. 7-9, where the radial line *OK* is drawn making an angle *XOK* (24 deg. 3 min.), the secant of which is 1.098. The spherical surface is divided into 10-deg. zones and the average zonal values of the candle power represented by the radial lines *Oa*, *Ob*, etc. If these mid-zone values are projected vertically onto the line *OK* the value of the flux in lumens in any zone will be represented by the corresponding distance, to the same scale as the polar curve is plotted, along the line *OK* measured from *O*. As an example of the manipulation of this method consider the

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[1] *Elec. Rev. and West Elec.*, vol. 58, p. 440, 1911.

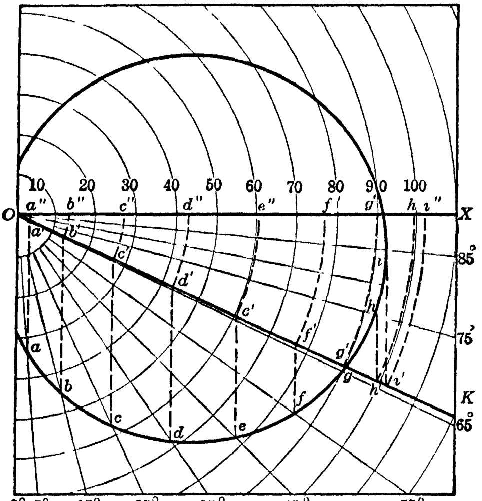

FIG. 7-9.—Modification of Wohlauer's method.

zone between the angles of 40 and 50 deg. from the vertical. Assume $Oe = 78$ to be the average intensity in this zone. Its projection on $OK = Oe'$, or 60.5 lumens. In the same way the flux in the 70 to 80-deg. zone will be 99 lumens. By adding the lumens in the different zones, the total lumens in the lower hemisphere may be obtained. The flux in lumens in the upper hemisphere may be found by projecting the mid-zone values upon the line *OK* or upon another line 24 deg. 3 min. above the horizontal, and proceeding as above.

The simplicity of this method is manifest. The only apparatus necessary is a pencil and a piece of paper and the only calculation is the simple addition of the nine or eighteen values obtained.

It is obvious that this method may be applied to any distribution curve plotted upon polar coordinate paper. In this case a series of vertical lines together with the radial line (Fig. 7-10) laid on a quadrant of transparent celluloid, tracing cloth, or similar transparent material will greatly facilitate operations.

Since the secant of 24 deg. 3 min. is approximately 1.1 (1.098), the mid-zone values may be projected directly onto the horizontal line and the sum of the projections multiplied by 1.1, and the same results obtained as above.

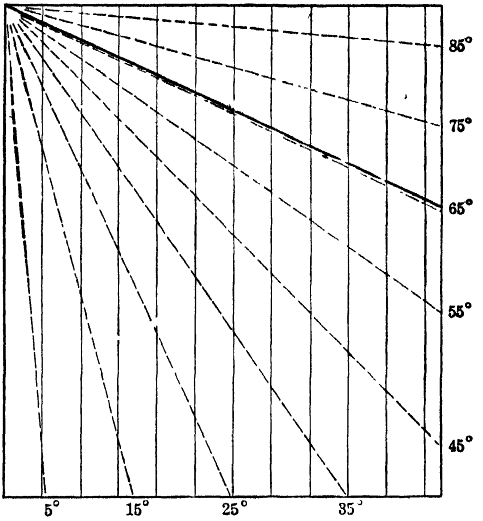

FIG. 7-10.—Auxiliary diagram applicable to any polar curve.

The mean hemispherical candle power may be found by dividing the lumens in the hemisphere by 2π and the mean spherical candle power by dividing the total light flux of the lamp by 4π.

Surface Sources of Light.[1]—There may be two distinct ideas concerning light: (1) a surface distribution of light over a luminous area of *brightness* or *specific quantity* b, and total quantity $Q = \int b dS$ and (2) a luminous flux filling the surrounding space and producing an illumination E on any body equal to the flux per unit of area, or

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[1] This section is abstracted with modifications from the paper of E. B. Rosa, *Bur. Standards Bull.*, vol. 6, p. 543, 1910, in which he acknowledges the writings of Blondel, Palaz, Liebenthal, Hering, Kennelly, Sharp, Hyde, and Jones.

$$E = \frac{F}{S} \tag{7-16}$$

So far, illumination and intensity have been defined in terms of the flux. Their values in terms of the *quantity of light on the surface of the luminous source* will now be determined.

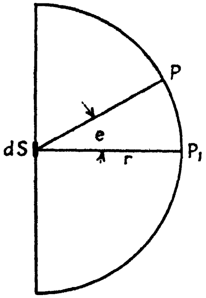

FIG. 7-11.—A small surface source.

The Unit Disk.[1]—The *illumination from a very small source* is inversely proportional to the square of the distance from the source and directly proportional to the brightness of the source. Hence for a luminous plane of area dS (Fig. 7-11) it is possible to write

$$E_{P_1} = \frac{Q}{r^2} = \frac{bdS}{r^2} \tag{7-17}$$

where Q is the total quantity of light on the disk and the radiation to P_1 at a distance r is normal. For a point P at an angle e from the normal the illumination would be

$$E_P = \frac{bdS \cos e}{r^2} = \frac{Q \cos e}{r^2} \tag{7-18}$$

The *total flux over the hemisphere illuminated by the disk* is

$$F = \int_0^{\frac{\pi}{2}} E_P 2\pi r^2 \sin e de = Q \int \frac{2\pi r^2 \sin e \cos e \, de}{r^2}$$

$$= \left(\pi Q \sin^2 e\right)_0^{\frac{\pi}{2}} = \pi Q \tag{7-19}$$

Thus the total luminous flux F from a small plane disk is π times the quantity of light Q on the disk.[2]

---

[1] By unit disk and unit sphere are meant a disk and sphere whose linear dimensions are negligible compared with the distance from source to receiver.

[2] In electrostatics the total flux is 4π times the quantity Q. The difference is due, first, to the fact that the luminous disk is supposed luminous on one side only and hence there is radiation only on one side, whereas the electric flux would be on both sides; secondly, the cosine law makes the average flux only half what it would be if the factor cos e were omitted.

The *average illumination over the hemisphere* of radius r is

$$\frac{F}{2\pi r^2} = \frac{Q}{2r^2} \tag{7-20}$$

whereas the maximum illumination E_n normal to the disk is Q/r^2. Thus the mean is half the maximum. The intensity I has been defined as the *angular rate of flux* in any particular direction. It is, therefore, proportional to the illumination produced in the given direction. Thus for the luminous disk

$$I_n = \text{maximum intensity (normal)} = Q \tag{7-21}$$

$$I_{hs} = \text{mean hemispherical intensity} = \frac{Q}{2} \tag{7-22}$$

$$I_s = \text{mean spherical intensity} = \frac{Q}{4} \tag{7-23}$$

Thus

$$F = \pi I_n = 4\pi I_s \tag{7-24}$$

That is, the intensity is numerically equal to the total quantity of light on the small disk *for all points on the normal.* It *decreases to zero* in passing 90 deg. away from the normal, having a mean value of half the maximum for the whole hemisphere, and is on the average only one-fourth the maximum for the whole sphere. It may, therefore, be said that the *hemispherical reduction factor* for the disk is one-half, and the mean *spherical reduction factor* is one-fourth, the disk being supposed luminous on one side only.

Since the total flux F from an area is πQ, where Q is the quantity of light on the area, the flux from a unit of area is πb. This is the radiation E'. Hence, in general,

$$E' = \pi b \tag{7-25}$$

For a small sphere of radius a the total flux is

$$\begin{aligned} F &= E' \times \text{surface} \\ &= \pi b \times 4\pi a^2 = \pi Q \end{aligned} \tag{7-26}$$

Also

$$F = 4\pi I$$

Therefore

$$I = \frac{Q}{4} \tag{7-27}$$

That is, for a unit sphere the intensity is one-fourth the quantity of light on the sphere. If the distribution of light over the sphere is not uniform, the *mean spherical intensity* is still one-fourth the total quantity of light on the sphere, as it is also for a disk. In other words, a sphere produces the same illumination at a given point as a disk of the same diameter and same brightness placed so that the radiation from the disk to the point is normal.

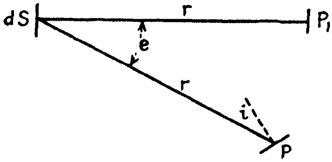

FIG. 7-12.—A small circular source.

Extended Source.—In Fig. 7-12 the illumination at P_1 in the normal to dS is

$$E_1 = \frac{bdS}{r^2} \tag{7-28}$$

while the illumination at P, the angles of emergence and incidence being e and i, respectively, is

$$E_2 = \frac{bdS \cos e \cos i}{r^2} \tag{7-29}$$

The cosine law is assumed to hold exactly for both surfaces.

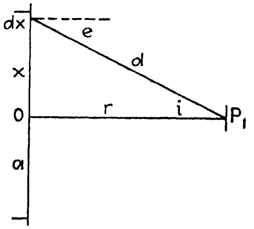

FIG. 7-13.—A large circular source.

To calculate the illumination due to a large circular disk of brightness b and any radius a on a small plane area P_1, normal to the axis of the disk and situated on the axis at distance r from the disk (see Fig. 7-13), the effect of each elementary circular ring of the disk is integrated. Thus in Eq. (7-29), putting $dS = 2\pi x dx$,

$$E = b\int_0^a \frac{2\pi x dx \cos e \cos i}{r^2 + x^2} \tag{7-30}$$

Since

$$\cos e = \cos i = \frac{r}{\sqrt{r^2 + x^2}} \tag{7-31}$$

$$E = \pi b \int_0^a \frac{2xdxr^2}{(r^2 + x^2)^2}$$

$$= \pi b\left(\frac{-r^2}{r^2 + x^2}\right)_0^a = \pi b\left(1 - \frac{r^2}{r^2 + a^2}\right) \tag{7-32}$$

or

$$E = \frac{\pi b a^2}{r^2 + a^2} = \frac{bS}{r^2 + a^2} = \frac{Q}{r^2 + a^2} \tag{7-33}$$

where Q is the product of the surface of the disk into the brightness b and is the total quantity of light upon the disk measured in candles. If the disk were very small, Q would be the same as the maximum intensity I_n of the source; but for an extended source a distinction must be made between the equivalent *intensity* I_0 and the surface integral of the *brightness* b, which is Q. The latter has been called the quantity of light upon the disk; it is proportional to the total luminous flux F coming from the extended source, and is equal to F/π (Eq. (7-19)). Q and F really measure the same thing, except that Q is located on the source and is measured in candles while F is located in the surrounding space and is measured in lumens; their ratio is constant as $F = \pi Q$ always.[1]

For the disk above mentioned, the illumination E on a small plane normal to the axis is proportional to the total quantity of light Q on the extended source (the circular disk) and inversely proportional to the square of the distance d from P_1 to the *edge of disk.* This holds true for all distances r from zero to infinity. Thus the *law of inverse squares holds generally* for the illumination along its axis due to a circular disk of any size, but the distance is measured not to the center of the disk, but to the edge.

---

[1] The total quantity of electricity on a disk of area S is equal to the integral of the surface density σ over the area.

$$
\begin{aligned}
Q &= \int \sigma dS \\
&= \sigma S
\end{aligned}
$$

when σ is uniform.

The brightness b of a source corresponds to the surface density of electricity σ, and the total quantity of light over a surface is, in the same way, the surface integral of b. Thus

$$
\begin{aligned}
Q &= \int b dS \\
&= bS
\end{aligned}
$$

when b is uniform over the area S.

For a sphere, the surface $S = 4\pi a^2$. Therefore, for a spherical source $Q = 4\pi a^2 b$, whereas the intensity $I = \pi a^2 b$. That is, the intensity I of a spherical source is one-fourth of Q, and is equal to the light on a disk of radius a and brightness b. That is, the intensity of the sphere is equivalent to that of a disk of the same diameter and the same brightness for points at a great distance.

Thus

$$E = \frac{I}{r^2} \text{ for a point source or a unit disk} \qquad (7\text{-}34)$$

and

$$E = \frac{Q}{d^2} \text{ for an extended disk} \qquad (7\text{-}35)$$

To illustrate the rate of variation of the illumination with the distance, let $a = I$, $r_1 = 1$, $r_2 = 5$ (Fig. 7-14).

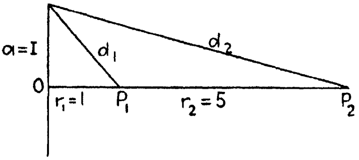

FIG. 7-14.—A large circular source.

In the first case for the point P_1, $E_1 = Q/d_1^2 = \pi b/2$.

In the second case for the point P_2, $E_2 = Q/d_2^2 = \pi b/26$.

Thus in the first case the distance is five times less and the illumination is thirteen times more, instead of twenty-five times more as it would be if the light Q were all concentrated at the center of the disk. If $r = 0$, the illumination is πb, or twice as much as at P_1, and not infinite as it would be at zero distance from a point source.

This theorem is useful in measuring the radiation from walls, as the radiating area may be quite large and the photometer relatively near.

Infinite Plane.—The *radiation from an infinite plane S* (Fig. 7-15) upon a unit area of a parallel plane T is found by integrating Eq. (7-32) to infinity. Thus

$$E = \pi b \int^{\infty} \frac{2x dx \cdot r^2}{(r^2 + x^2)^2}$$
$$= \pi b \left(\frac{-r^2}{r^2 + x^2} \right)_0^{\infty} = \pi b \qquad (7\text{-}36)$$

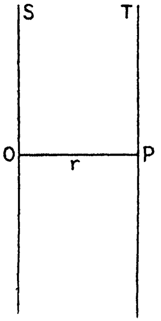

FIG. 7-15.—Radiation from an infinite plane on a unit area.

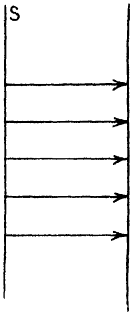

FIG. 7-16.—Radiation from an infinite plane on an infinite area.

Thus the flux density or *illumination* at any point P on the T plane is π times the brightness b on the radiating plane S and is independent of the distance r.

From each unit of area of S having a brightness b the total flux is πb, as shown above. The resultant flux at all points is the same as though the total flux πb from each unit of area of S was confined to a cylindrical tube of unit area perpendicular to S, in which case the flux density would, of course, be constant at all sections, *i.e.*, at all distances (see Fig. 7-16).

Unit Length of Cylinder.—Suppose a light source in the form of a very long cylinder of radius a and uniform brightness b. It is desired to determine experimentally its total luminous flux F. Suppose one has measured by means of a photometer the equivalent intensity I_1 of unit length of the cylinder (screening the photometer from all but a short section of the cylinder). We are to calculate the total flux F_1 from I_1. The unit length of cylinder will produce the same illumination at a distance as a rectangular plane of breadth $2a$ and height unity of brightness b equal to that of the surface of the cylinder. Hence the equivalent intensity I_1 is equal to $2ab$ and the illumination produced on a photometer screen at distance r is

$$E = \frac{2ab}{r^2} = \frac{I_1}{r^2} \tag{7-37}$$

The quantity of light on the cylinder per unit of length is b times the surface, or $2\pi ab$, and the total flux F is π times the quantity. Thus we have

$$F_1 = 2\pi^2 ab \tag{7-38}$$
$$I_1 = 2ab \tag{7-39}$$
$$F_1 = \pi^2 I_1 \tag{7-40}$$

Thus to obtain the total luminous flux F_1 from the measured value of the equivalent intensity of a unit of length of the luminous cylinder we multiply this intensity I_1 by π^2, instead of multiplying by 4π as in the case of a sphere.

The spherical reduction factor of a short cylinder (the convex surface only being luminous) is therefore $\pi^2/4\pi = \pi/4 = 0.785$. This would be nearly true for an incandescent lamp having one or more straight filaments. The value for a hairpin filament would be only slightly larger.

If the cylinder is long, we should then get the total flux F by multiplying F_1 by the length of the cylinder. This demonstration is, of course, based on the assumption that the cosine law holds for the cylinder. If the source is a long tube, like the Moore light, the result would be subject to any modification dependent on its departure from the cosine law.

Thus while the total flux F is always π times the quantity Q of the source, it is not always 4π times the intensity It is 4π times the intensity I for a point source or sphere, $\pi^2 L$ times the equivalent intensity I_1 (measured at a relatively great distance) of unit length of a long cylinder, L being the length, and πS times the equivalent intensity I_1 of unit of area of a plane, S being the area of the plane.

It is, however, always 4π times the *mean spherical intensity* of the given source. The illumination produced by a short cylinder is approximately inversely proportional to the square of the distance. For all distances greater than five times the length the departures are not greater than 0.2 per cent in a particular case worked out by Hyde; the diameter of the cylinder in this case was one-tenth the length. The exact expression for the illumination due to a finite cylinder is not simple.

Infinite Cylinder.—In a manner similar to our treatment of infinite surface sources, we may consider the flux from an infinite circular cylinder of uniform brightness b and radius a.

The flux coming from unit length of the cylinder is πb times the area. Hence $F = 2\pi^2 ab$ whereas the flux falling on the inner surface of a concentric cylinder of radius r is E times the area, E being the illumination. Hence for a unit of length of the cylinder $F = 2\pi r E$. Therefore

$$E = \frac{\pi ab}{r} = \frac{Q}{2r} \tag{7-41}$$

Thus the illumination due to an infinite cylinder varies *inversely as the distance.* This is intermediate between the case of the point source, for which E varies inversely as r^2, and the infinite plane, where E is independent of the distance.

The quantity Q for the luminous cylinder is b times the surface. Therefore the *quantity per unit of length is*

$$Q_1 = 2\pi ab \tag{7-42}$$

The total luminous flux F, as stated above, is $2\pi^2 ab$. Hence the total flux per unit of length F_1 is π times the quantity, or

$$F_1 = \pi Q_1 \tag{7-43}$$

or for any portion (or the whole) of an infinite cylinder of uniform brightness the total flux is π times the quantity; that is,

$$F = \pi Q \tag{7-19}$$

as shown for a circular disk.

A Large Spherical Source.—If a source S_1 (supposed a portion of a spherical surface of radius r_1) has a brightness b and subtends

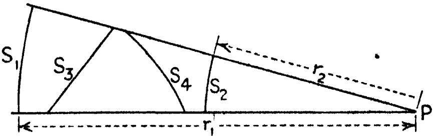

FIG. 7-17.—Section of large spherical source.

a small solid angle ω, the illumination which it produces at P (Fig. 7-17) is

$$E = \frac{bS_1}{r_1^2} = \frac{b\omega r_1^2}{r_1^2} = b\omega \tag{7-44}$$

A second surface S_2 of the same brightness will produce the same illumination at P provided it subtends the same angle ω. A third surface S_3 at any angle will also produce the same illumination at P if it has the same brightness b and subtends the same solid angle ω.

For the radiation of each element dS_3 is

$$\frac{bdS_3}{r_3^2}\cos e = \frac{b\omega r_3^2}{r_3^2} = b\omega \tag{7-45}$$

as before. So also with the curved surface S_4. In every case the greater distance from P on the inclination of the angular position is compensated by the greater area included within the given (small) solid angle.

Now calculate the illumination at P due to a large luminous sphere of radius a and brightness b, r being the distance from P (Fig. 7-18) to the center of the sphere. Let the solid angle APB subtended at P by the sphere be subdivided into a large number of elementary solid angles. Each of the latter encloses an area, as S_1, on the surface of the sphere, and also a corresponding area S_1', on the circular disk AB. As has just been seen, the illumination produced at P by each spherical area S_1, S_2, etc., is exactly the same as that produced by the corresponding plane areas S_1', S_2', etc., of the disk, if the brightness b is the same for the disk as for the sphere. Therefore the illumination at P due to the entire sphere is the same as that due to the disk AB, and the latter may be calculated by Eq. (7-35); that is,

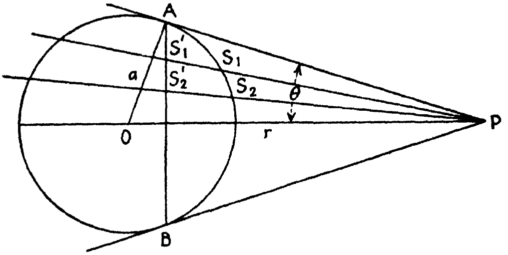

FIG. 7-18.—A large spherical source.

$$E = \frac{Q}{d^2}$$

where Q is the quantity of light on the disk and d is the distance AP from the point P to the edge of the disk. Q is equal to b times the area of the disk, or

$$Q = \pi(a \cos \theta)^2 b \qquad (7\text{-}46)$$

$$d = r \cos \theta \qquad (7\text{-}47)$$

therefore

$$E = \frac{Q}{d^2} = \frac{\pi a^2 b}{r^2} = \frac{1}{4}\frac{Q_s}{r^2} = \frac{I_s}{r^2} \qquad (7\text{-}48)$$

where $Q_s = 4\pi a^2 b$ is the quantity of light on the sphere and is constant for all distances, and I_s is the intensity of the equivalent point source. Therefore the illumination produced by a *sphere of any size* is inversely proportional to the square of the distance measured *from its center,* and is equal to the intensity of a point source (or unit sphere) having the same total amount of light divided by the square of the distance. In other words, the inverse-square law holds just as rigorously for large spheres as for points (always, of course, assuming the cosine law to hold for the spherical surfaces, and the brightness b to be uniform over the sphere). When P comes very near to the surface, the area

AB of the sphere (Fig. 7-19) available for illuminating P is very small, but the distance is just enough less to counterbalance. When P comes up to the surface, $r = a$ and

$$E = \pi b \tag{7-36}$$

the same as for an infinite plane, to which the sphere is equivalent when the distance from the surface is reduced to zero.

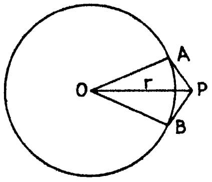

Fig. 7-19.—A large spherical source. (P near.)

The same result is reached more simply as follows:

A luminous sphere of radius a and uniform brightness b gives off a total flux $F = 4\pi a^2 \times \pi b = 4\pi^2 a^2 b$. This produces an illumination on the inner surface of any concentric sphere, which by symmetry will be everywhere the same, and $F = 4\pi r^2 E$. $\therefore$

$$E = \frac{\pi a^2 b}{r^2} = \frac{I}{r^2} \tag{7-49}$$

Therefore the *illumination produced by a sphere* of uniform brightness is inversely proportional to the square of the distance from the center for all distances from the surface of the sphere to infinity.

A Hollow Spherical Source.—From what precedes it is seen that the illumination at any point P due to the hollow hemisphere ACB (Fig. 7-20) is the same as that due to the circular disk AOB. The latter is

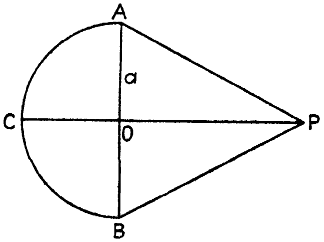

Fig. 7-20.—A hollow spherical source.

$$E = \frac{\pi a^2 b}{AP^2} \tag{7-50}$$

When OP is reduced to zero, the illumination due to the disk is πb, and hence the illumination at O on an elementary plane area in the diametral plane is π times the brightness b of the surface of the sphere. It has already been seen that the total flux from a unit of surface of brightness b is πb. Hence the total flux through unit area S at O, due to the hemisphere, is equal to the total flux through the hemisphere due to the luminous unit area S, the brightness b being the same in each case.

SPHERICAL PHOTOMETRY

Spherical Photometers.—It is obvious that where the spherical-light values of a large number of lamps are required and the spherical reduction factor is not accurately known, and especially in the photometry of lamps where the light fluctuates considerably, it is desirable to employ means whereby the result can be obtained by one photometrical setting. This is accomplished very satisfactorily by means of an integrating photometer of either the mirror or the spherical type.

The Matthews Photometer.—The mirror photometer was first designed by Prof. Matthews for use in the laboratories of Purdue University. By means of it the mean spherical candle power of any source can be determined by one reading, but it was especially intended for arc-light photometry.

In order to produce on the photometer screen an illumination proportional to the mean spherical intensity of the source, it is necessary to direct toward the photometer beams of light from various angles in the vertical plane. It is furthermore essential that these rays, representing the intensity of light at the respective angles, be reduced in intensity in the ratio of the sine of the angle which the rays make with the vertical, in order that the light from each mirror shall be proportional to the area of the zone which it represents. In developing this method, a ring of 24 large trapezoidal mirrors, placed one every 15 deg., surrounds the arc. The inclination of the mirrors to the arc is such that 24 images of the lamp are presented to the eye placed at the photometric device. Direct rays from the lamp are intercepted by a black screen. The reduction of the light in the ratio of the sine of the vertical angle is accomplished by means of a polygonal glass disk composed of as many sectors as there are mirrors and which are smoked sufficiently to give the desired absorption.

One condition essential to the success of this piece of apparatus is that the screen shall receive through each sector only the light from its corresponding mirror. The sector disk can be adjusted by replacing the screen by a cardboard pierced by a small opening and, by sighting through this hole, the disk can be placed with reference to the mirrors. Mirrors of good-quality French plate glass were used and their reflection coefficients were carefully determined for the angle of incidence at which they were used; the maximum difference from the mean value of 0.815 was only ±2.9 per cent, which was corrected by smoking the corresponding sectors. The smoking of the disks was accomplished by burning small quantities of turpentine in a receptacle in which the sector, with a guard ring to ensure even density, was placed in a vertical position.

In the photometer described by Prof. Matthews, a plan of which is shown in Fig. 7-21, the light from the standard lamp, because of the small size of the room, was reflected onto the screen by means of another mirror *M*. The illumination on the side of the screen toward the arc lamp, being very intense, was reduced by means of a rotating disk provided with a large number of slots.

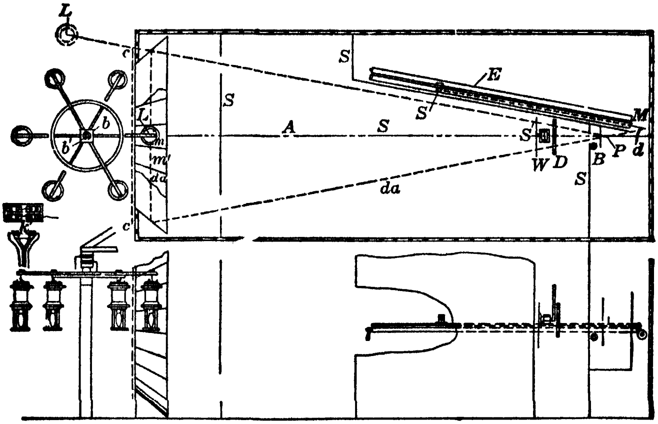

FIG. 7-21.—The Matthews photometer.

The Leonard Photometer.—The Leonard photometer is of more recent design than the Matthews photometer, although similar in theory and construction, the chief difference between the two being that the mirrors of the Leonard photometer are located at intervals corresponding to the middle points of successive zones of equal areas. Thus the average of the light thrown upon the screen represents directly the mean spherical or the mean hemispherical candle power, as the case may be, without intervention of smoked sectors.

Ulbrich's Spherical Photometer.—This photometer also permits the measurement of the mean spherical candle power of a lamp by a single setting. It consists, in part, of a large sphere, with its inner surface painted white. The source of light to be measured is placed inside of this sphere and the illumination at an opening in the surface of this sphere (the direct rays being intercepted by a screen) is proportional to the mean spherical candle power of the lamp. A globe of this kind integrates very successfully the illuminating effect of any source. It involves, in addition, a photometric device and a standard incandescent lamp.

The general theory of the spherical photometer is as follows: When a source of light is placed inside a spherical shell having a mat surface, the light received by any part of the interior surface can be considered in two parts: (1) that coming directly from the lamp, and (2) the light received from the remainder of the interior surface of the sphere after one or more reflections. The quantity (1) is that which is measured in the ordinary photometer which determines the intensity of light emitted in any one direction, and is not considered at all in the globe photometer. According to the theory of the globe photometer, the quantity (2) is constant all over the surface of the shell, and is proportional to the total amount of light emitted by the lamp, quite independent of its position in the shell.

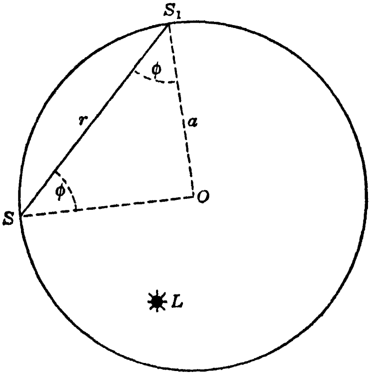

FIG. 7-22.—The hollow sphere.

Suppose a hollow sphere[1] (Fig. 7-22) of uniform surface having a coefficient of diffuse reflection m.

$$1 - m = \text{absorption}$$

Let E = illumination at S

$E' = mE$ = radiation from S

$b = \frac{mE}{\pi}$ = brightness of S

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[1] LIEBENTHAL, *Praktische Photometrie*, p. 301, 1907, Vieweg, Brunswick.

The flux falling on S_1 due to S is

$$S_1 dE_1 = \frac{bSS_1 \cos^2 \varphi}{r^2} = \frac{mE}{\pi} \cdot \frac{SS_1 \cos^2 \varphi}{r^2} \tag{7-51}$$

But

$$r = 2a \cos \varphi$$
$$r^2 = 4a^2 \cos^2 \varphi$$
$$\frac{\cos^2 \varphi}{r^2} = \frac{1}{4a^2}$$

Therefore

$$dE_1 = \frac{mE}{\pi} \cdot \frac{S}{4a^2} \tag{7-52}$$

and this is the same for every element of the sphere. Hence *every element* illuminates all other elements equally. Therefore the *indirect* illumination of the sphere must be the same everywhere, no matter how unequal the direct illumination may be; *i.e.*, a light at L illuminates the sphere unequally, directly. But that part of the total illumination due to diffuse reflection is, notwithstanding, everywhere equal.

A light of mean spherical intensity I sends out $4\pi I$ lumens.

Of this there are reflected, first, $4\pi mI$ lumens.

Of this there are reflected, second, $4\pi m^2 I$ lumens.

Of this there are reflected, third, $4\pi m^3 I$ lumens, etc. Therefore the total amount of flux reflected is

$$4\pi Im(1 + m + m^2 + m^3 + \cdots) = 4\pi I \frac{m}{1 - m} = F_2 \tag{7-53}$$

Hence the secondary illumination everywhere equal on the surface of the sphere is

$$E_2 = \frac{F_2}{4\pi a^2} = \frac{mI}{(1 - m)a^2} \tag{7-54}$$

Thus the indirect illumination is proportional to I, and the lamp of intensity I may be anywhere in the sphere. It is equal to $\frac{m}{1 - m}$ of what the direct illumination would be if the source were placed at the center of the sphere. For example, let a 16-candle-power lamp be placed within a sphere having a radius of 1 m. and a coefficient of diffuse reflection of 0.8.

Then $I = 16$

$a = 1$ m.

$m = 0.8$

$$E_2 = \frac{0.8}{0.2} \times \frac{16}{1} = 64 \text{ meter-candles}$$

$$E_1 = \frac{I}{a^2} = 16 \text{ meter-candles, if lamp is in the center}$$

$$E = E_1 + E_2 = 80$$

Thus the total illumination is five times what it would be if the walls were perfectly black. This may be put in another way; of the total illumination of 80 meter-candles, 20 per cent is absorbed by the walls. Therefore the lamp or source must supply only one-fifth of the total, just enough to make good the constant loss.

If the lamp be removed to the surface of the sphere so that the center of the source is directly in the surface, then a single measurement will give a value proportional to the mean hemispherical candle power, the ratio of proportionality being one-half that in the determination of the mean spherical candle power.

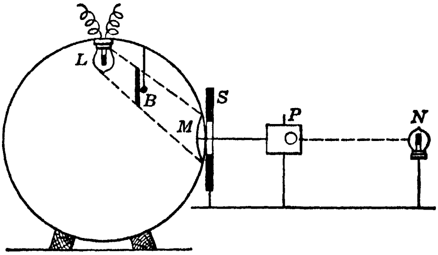

FIG. 7-23.—The globe photometer.

There are two sources of error in this method; one is likely to occur if the lamp is not in the center of the surface, while the other is due to the nontransparent fittings of the lamp which intercept part of the light. Experiments show that errors due to the latter cause greatly outweigh those due to the former, but that a compromise may be made sufficient for all practical purposes if the lamp is not supported at the center but at a distance of 8 or 15 per cent of the diameter from the top of the inner surface of the sphere, also by making the globe very large.

The construction of this photometer is shown in Fig. 7-23, where *L* and *N* are the two lamps, *P* the photometric device, *S* a screen whose aperture can be varied, and *M* the window of some translucent material protected from the direct rays of the lamp by the screen *B*.

Experiments with globe photometers give results very consistent with those obtained from point-to-point readings, and tests of a great many different sources of light show that the mean spherical candle power can be obtained by this arrangement with an error of not more than 3 per cent. The apparatus can be calibrated by a lamp of known mean spherical candle power placed at the center of the sphere. The most satisfactory surface for the inner side of the sphere appears to be a coating of lithopone (barium sulphate), and more consistent results are obtained by using a translucent screen of milk glass. This instrument highly recommends itself for the photometry of arc lamps where the distribution of light is not desired, since the fluctuating value of the candle power due to the continual changing of the arc makes arc-lamp photometry, by the ordinary distribution methods, slow and tedious.

The icosahedron represents a modified form of the globe photometer. It is constructed of 20 equilateral triangles, of which 15 form the body of the apparatus and the remaining 5 form the door, making its construction easier and more economical. It is some 10 ft. high. In theory and operation, however, it is similar to the globe photometer.

The Kennelly Lumenmeter.—An ingenious arrangement has been designed by Kennelly for determining the mean spherical intensity or the total luminous flux from a lamp by a single reading. It can be used for the photometry of either incandescent or arc lamps, but when used for the former it has an auxiliary device for rotating the lamp.

It consists essentially of two revolving mirrors and a disk containing a series of openings proportional to the areas of the zones from which the light passing through them comes when the mirrors revolve. The mirrors are placed 180 deg. apart and revolve in a vertical plane about the source of light as a center. The openings in the sectored disk are placed in the paths of the rays reflected by the mirrors onto the photometer screen. The theory of this instrument involves that of the rotating sectored disk and the mirror photometer. It is obviously immaterial with the rotating sectored disk whether the disk rotates and the beam of light is at rest or vice versa. In the mirror photometer the intensity of the light which strikes the screen from the various zones is made proportional to the light flux in the respective zones. The mirrors of the lumenmeter are driven by a motor and must revolve at sufficient speed so that no flicker is noticeable on the screen.

The Photoelectric Cell Integrator.[1]—Light-sensitive cells have been applied as shown in Fig. 7-24 to measure the amount of light from a lamp. Since the cells lie in a vertical plane, provision is made for rotating the unit in order to obtain results proportional to the average candle-power values in the different directions. The cells are equipped with apertures which correct their output in proportion to the areas of their respective zones. These cells are connected in multiple and their combined output is indicated on a microammeter. Thus the total output of the unit in lumens will equal the microammeter reading multiplied by a constant. The usual precautions necessary for accurate measurements must be taken. It is very important to prevent

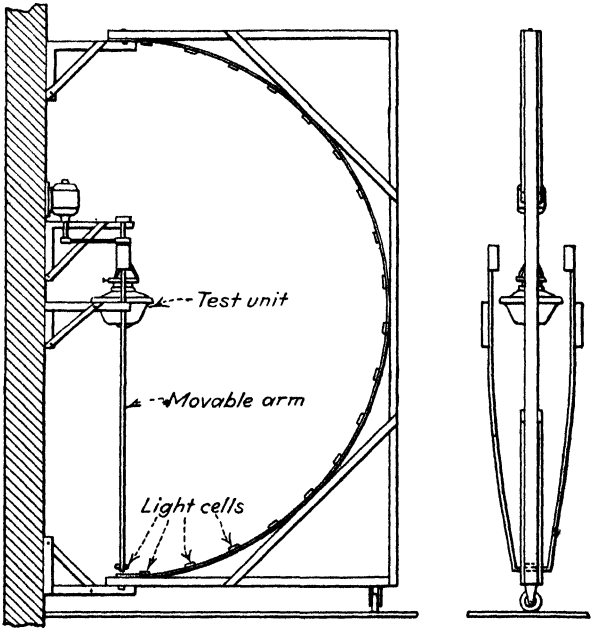

FIG. 7-24.—Principle of operation of photoelectric integrator.

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[1] DOWS and BAUMGARTNER, *Trans. Illum. Eng. Soc.*, vol. 30, p. 476, 1935.

any light that might come from the side walls, floor and ceiling from being reflected back into the cells.

The Distribution Reflectometer.[1]—To measure the reflection factor of a flat surface it has been the practice to project a normal beam of light on a sample of the surface and measure the intensity of the reflected light through an angle of 90 deg. from the projected beam as a starting point, by means of the visual-distribution method. Also accurate results require the services of a trained operator. It is obvious that a light-sensitive cell mounted on a movable arm traveling over the various angular divisions throughout the 90-deg. quadrant can replace the visual method. The total light reflected may be obtained by multiplying the readings of the microammeter in the cell circuit by the proper zone constants times, of course, the constant of the instrument and adding the results.

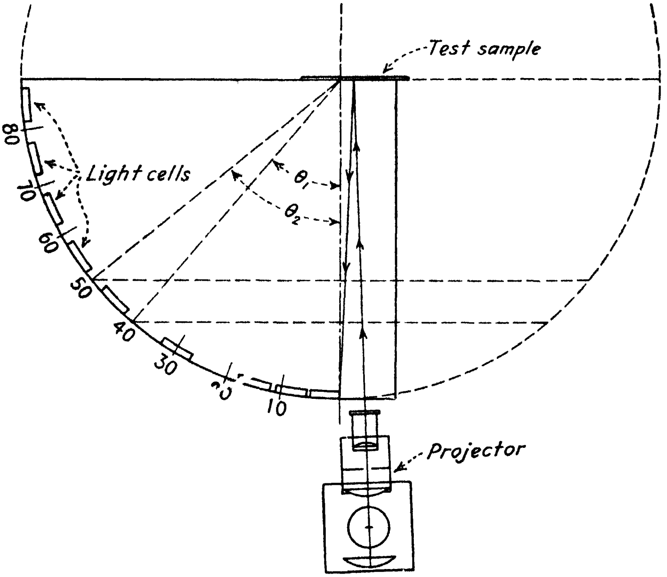

FIG. 7-25.—Principle of operation of distribution reflectometer.

It will be now apparent that the same result can be better accomplished by permanently mounting cells at the various angular position as shown in Fig. 7-25. Inasmuch as the light striking a very specular sample perpendicularly would be reflected back into the projector, it is necessary to shift the beam slightly off this line as shown in the figure. The application of the proper zone constants can be accomplished by placing screens having apertures proportional to the areas of the respective zones over the light-sensitive cells. The cells are all connected in multiple and the cumulative output read on the microammeter is indicative of total light reflected from the sample.

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[1] *Ibid.*

Each cell may be equipped with a light-tight housing which will admit only light from the test sample thus making a darkroom unnecessary. The inside surface of the housing should be painted a flat black to minimize the effect of reflected light from the interior surfaces.

The use of a movable arm with a single cell mentioned above moving through the 90-deg. quadrant becomes valuable in exploring the type of distribution of reflected light and makes it possible to readily classify various samples as to degree of diffusion or specularity.

Testing Specifications for Lighting Equipment.—The Illuminating Engineering Society in cooperation with other interested organizations has developed specifications for testing diffusing glassware, narrow beam projectors, and asymmetric equipment.[1] Some of the principal points of these tests are indicated in the following illustrations.

In the report on a *luminaire with diffusing glass* the dimensions *a*, *b*, *c*, etc. (Fig. 7-26) should be given and also the brightness in candle power per square inch at the points *D*, *B*, *L*, etc., and in the directions indicated by the respective arrows. There should also be a complete description of the unit.

The photometric data may be arranged, recorded, and illustrated as in Fig. 7-26. It will be seen that candle-power curves are shown for the bare lamp and for the luminaire. The various data for the latter are determined and recorded in systematic order. All tabulated values and curves should be on the basis of the rated lumens for the lamp as given by the lamp manufacturers.

The procedure for *testing floodlights* and calculating and reporting the results should include complete description and details of the floodlight including dimensions of the unit and of the lamp and its location. A floodlight beam is inclined to be uneven and, if so, a complete exploration of the beam may be necessary to determine its true formation and intensity. This can be done

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[1] *Trans. Illum. Eng. Soc.*, vol. 28, p. 479, 1936.

REPORT NO. **ORDER NO.** **PLATE NO.**

CANDLEPOWER DISTRIBUTION

NO. **GLOBE***

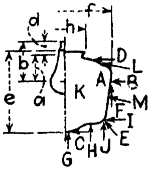
Tested in compliance with I.E.S. Standard Testing Specifications

Rendered to

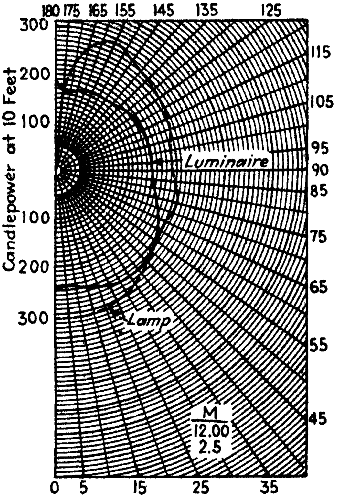
Number—Submitted 100; Inspected and weighed 25; Tested 6.
Light output range 82 to 83. Average 82.5 per cent.
Lamp—200 watts;115 volts; 3280 lumens; PS30 clear gas-filled bulb; C-9 filament; medium base; general service.
Surface covering globe opening; reflection factor 0.40.

DIMENSIONS OF LUMINAIRE

a 4 in.
b 6
c
d 2
e 11⅛
f 13¾
h 6



WEIGHT OF GLASS 55 to 64 oz.
Test Sample 60 oz.



LUMINAIRE DISTRIBUTION DATA

Mean vertical

Mid-zone angles	Apparent candle-power at 10 ft.	Zonal lumens	Mid-zone angles	Apparent candle-power at 10 ft.	Zonal lumens
180° Zen.	183		90° Nor	200	
175°	165	16	85°	201	219
165°	171	48	75°	216	229
155°	178	82	65°	233	231
145°	179	112	55°	252	226
135°	187	145	45°	267	207
125°	195	175	35°	271	170
115°	197	195	25°	266	122
105°	200	212	15°	252	71
95°	200	218	5°	241	23
			0° Nadir	246	

LIGHT FLUX VALUES

Zone	Lumens		Per cent total lumens bare lamp	Per cent light output
	Lamp	Luminaire		
0°- 60°	877	819	25	
0°- 90°	1665	1498	46	
90°-180°	1615	1203	36.5	825.
0°-180°	3280	2701	82 5	

LUMINAIRE BRIGHTNESS

MILLILAMBERTS AND CANDLEPOWER PER SQUARE INCH
The arrows indicate the location and angle of view

Locations	A	B	C	D	E	F	G	H	I	J	K	L
Ml.	1000	1200	940	1200	1150	680	980	1000	1050	820	1100	1100
Cp. per sq. in.	2 1	2 5	1 9	2 5	2 4	1.4	2.0	2.1	2.2	1.7	2.3	2.3

* Identification No. 2074.

TESTED BY________ **PLOTTED BY**________ **COMPUTED BY**________ **CHECKED BY**________ **ISSUED** Feb. 15, 1929

FIG. 7-26.—Typical photometric report.

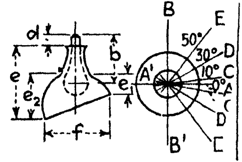
by locating the tests points in rectangular areas across the beam. The axis of the beam can be located only after the test has been completed, therefore, it is necessary to estimate the position of the axis by visual observation of the edges of the beam or the intensity of the illuminated field before locating the test points.

Because of the filament images in the beam, too small a test area may give erratic results. For this reason an integrating device should be used which will indicate the average illumination over one square degree (20.94 by 20.94 in. at 100-ft. testing range). In addition to these tests in rectangular areas over the area of the beam, it is recommended that candle-power values be obtained along eight equally spaced radial lines carried out to the extreme angular edge of the stray light.

CANDLEPOWER DISTRIBUTION

WATTS	200	VOLTS	115	SERVICE	General	BASE	Medium
LAMP	Masda C	LUMENS	3340	FILAMENT FORM	C-9	BULB	PS30 Clear

TESTED ACCORDING TO I.E.S. STANDARD SPECIFICATION



DIMENSIONS

- b 6 in
- d ¾ in.
- e 9⅛ in.
- e_1 3 in.
- e_2 6½ in.
- f 9⅛ in.

SPECIAL INFORMATION

Mirrored glass reflector

Selection by· Manufacturer

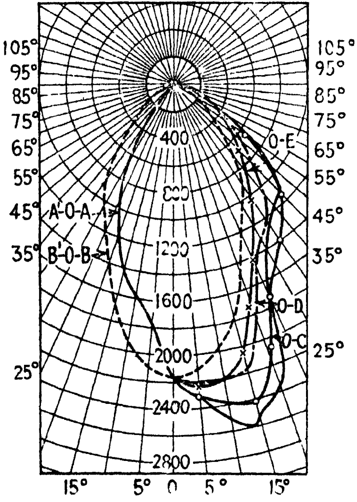
Number of units tested: One

Exceptions to I.E.S. specifications: none

LABORATORY DETAILS

Photometric distance—10 ft.
Lamp not rotated

Tested in five planes in two quadrants
O-B and O-B¹ averaged



CANDLEPOWER

Vert. Angle	O-A	O-A¹	O-B	O-C	O-D	O-E
0	2160	2160	2160	2160	2160	2160
5	1780	2320	2102	2320	2214	2240
15	1432	2520	1660	2418	2178	2051
25	944	1688	1188	1712	1444	1428
35	424	1240	888	1400	1226	1020
45	12	1132	436	1134	810	676
55	0	696	256	660	525	502
65	0	292	4	304	292	296
75	0	196	0	206	116	0
85	0	4	0	0	0	0
90	0	0	0	0	0	0

Vert. angle from Nadir degrees	Per cent lumens (in terms of lamp alone) horizontal angle from right to left of plane of symmetry degrees			
	20-20	40-40	60-60	90-90
0-20	2 9	5 7	8 3	12 2
0-40	8 6	16 2	23 2	32 9
0-60	13 5	24 7	35 0	48 3
0-90	15 2	27 9	39 2	33 0

Total lumens 2740
Total lumens bare lamp 82

ADDITIONAL READINGS

Lab Report No. 3635
Order No. 2259
Plate No. 23595
checked by· *E M. S.*

July 7th, 1930.

FIG. 7-27.—Typical distribution curve and photometric report.

The area of one square degree is 0.000305 for unit radius spherical shell. The product of this factor times the square of the distance from the collecting device to the floodlight, in feet, times the foot-candle value is the average lumens in the square degree area of the collecting device. Obviously if the stations are more or less than 1 deg. apart the proper factors must be used to determine the total lumens.

For asymmetrical reflecting units a complete test should show the candle-power values in five vertical planes through the axis of the lamp, as indicated in Fig. 7-27. The readings in these planes being at angles of 0, 5, 15, etc., deg. from the nadir as shown. A simplified test may include readings in three vertical planes. One set of readings in the plane of symmetry and the others at 45 and 90 deg., respectively, and at the same 11 vertical angles as in the complete test.

CHAPTER VIII

PRINCIPLES OF INTERIOR LIGHTING

An interior illuminating system may very properly be considered a *complex problem* made up of a number of subordinate problems. The elements to be considered are: the class of room and the service for which the illumination is required; the luminaire best suited for the service; the effect of the color and the reflection of ceilings and walls; together with intensity, distribution, diffusion, color, intrinsic brightness, glare, shadow, etc.

With these various factors in mind the question arises as to what constitutes the essentials of a *good lighting installation.* Following the order given above, it is easy to formulate a rule which will apply to all but exceptional cases. The *intensity* should be ample to enable one to see clearly and distinctly, and the *distribution* should be such that the illumination over part of the room at least will be nearly uniform. The *light* should be soft and well diffused. The *color* of the light preferable depends upon the class of service and the tastes of the individual. A light approaching daylight in quality or inclined toward the yellow will, in general, be found satisfactory. The *sources of light* should be placed well above the range of vision, their intrinsic brightness reduced by diffusing glassware, and objects capable of high specular reflection removed from the range of vision. *Shadows* are necessary for distinguishing outlines, but such shadows should be toned down and be not too abrupt or dense.

Luminous sources should be so placed that the rays will not pass directly into the eye. The result of sources thus wrongly located is that objects back of the source, with direct rays, and the reflecting medium, if the rays are reflected, are more or less indistinct. Light coming from an unusual angle should be avoided. Light is usually received from above and the retina becomes accustomed to light from that direction. Light reflected into the eye from below, as from snow, or the direct rays, as from footlights, may not only cause fatigue but sometimes temporary blindness. *Streaks of light* and *sharp contrasts* may be injurious to the eye, the effect being similar to that of a flickering light.

Modern Lighting Standards.[1]—Good lighting, in conformity with the modern concept, should comply with these six standards:

1. General lighting should effectively illuminate all objects and areas to be seen with due regard to their relative importance in the interior composition. This implies a general level of illumination adequate for eye comfort throughout the room; elimination of dark shadows and sharp contrasts while preserving soft shadows for roundness and relief, and lighting emphasis on those parts which should command first attention.
2. Light sources should be subordinated in visual importance to the things they are intended to illuminate, except in rare instances where the light source itself is wanted as the dominant decorative element. Unless so effectively concealed or counterlighted that they are not apparent, light sources have extremely high attention value and readily dominate the scheme when in use. If visible they should usually be so disposed as to attract the eye to the major features of the room rather than divert attention to themselves.
3. Glare must be completely eliminated. Glare is the result of intense brightness in concentrated areas within the direct line of vision. It may be produced by excessive brightness of visible lights, by reflections of bright lights from polished or only slightly diffusing surfaces, and occasionally by extreme contrasts of light and shade. To assure its complete elimination it is usually necessary to employ means of diffusing light at its source or to use finishing materials throughout the room that diffuse or absorb rather than reflect light sharply.
4. The level of illumination should be adequate for the type of eye work required in the room. Local lighting may supplement general lighting to provide adequate illumination of work at machines, desks, reading tables, and other fixed points, but this high-level local lighting should always be accompanied by enough general illumination to minimize contrasts and eyestrain.

It may be noted here that there can be no such condition as over-illumination from artificial sources provided there is no glare. Outdoor daylight levels run up to 10,000 units; indoor natural lighting to several hundred. Rarely does artificial lighting today exceed 20 units, though the tendency is upward and for some purposes may reach 100 or more units.

5. General illumination should be related to or controlled to suit the occupant's mood. There are important psychological reactions to

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[1] *Am. Architect*, November, 1934, Am. Inst. Architects File No. 31-F.

light. Worship, introspection, contemplation, and physical relaxation are aided by relatively low lighting levels. Gaiety, keen thinking, and great mental and physical activity are favored by high levels. In theatres, houses, and some types of restaurants it is particularly important to control lighting according to mood; in stores and shops and in some institutional buildings it is necessary to employ the amount of light that will produce the most favorable psychological reaction; in offices, factories, schools, and shops where work is done it is essential to select illumination levels that will eliminate eyestrain.

6. Appearance of light sources should be carefully related to the style, decorative treatment, and general composition of the room. In style, shape, and finish visible fixtures or luminaires, or the means employed to conceal hidden sources, should harmonize, both lighted and unlighted, with the architectural character of the room.

There are four general systems of interior lighting: (1) direct, (2) semidirect, (3) semi-indirect, and (4) indirect.

In the direct lighting system the light passes direct to the working plane. The lamp is, in general, equipped with a reflector, shade, or diffusing media. Direct lighting practice may extend from spotlight and concentrating types of equipment throughout an almost countless number of reflecting and diffusing luminaires to extended light-source areas such as large glass panels and skylights. To provide high values of illumination without glare with open-type reflectors and diffusing globes, though most efficient, is difficult unless care is taken in locating and shielding such sources. This has led to the development of many modern systems such as louvered downlights in concentrated reflectors and lens control to direct the light downward, permitting high mounting and allowing a minimum of light in the direction of the observer. The proper location of the lighting units is very important to produce good distribution, to avoid harsh shadows, and to minimize glare. Large area sources of low brightness and of good diffusion produce excellent results in toning down the shadows and in reducing both direct and reflected glare. Types of direct lighting units with data concerning them are shown in illustrations 1 to 9, Figs. 8-4 and 8-5.

In the semidirect lighting system the greater part of the light passes direct to the working plane but also a considerable amount of light reaches the ceiling and walls, *e.g.*, with the use of opal enclosing and prismatic glass globes. Such units are likely to be too bright unless oversize globes are used. They should be placed, in general, close to the ceiling and as far out of the range of vision as possible. They are best suited to rooms with high ceilings. Such units, if placed low, from necessity, may be greatly improved by the addition of parchment shades to reduce the brightness toward the eye level and at the same time improve the efficiency of the system with reference to the work plane. Illustrations 10 and 11, Fig. 8-4, show the principle of this system.

A high level of uniformly distributed illumination is desirable but unless this is accompanied by a freedom from glare from the light source only very little is accomplished. The objection has been advanced that a large room containing a great many white glass diffusing globes as lighting units gives the appearance of being a sea of whiteness, and is therefore distracting. Unfortunately not only have there been many cases of improperly installed diffusing glass enclosing globes but the enclosing globe has often been called upon to serve under conditions which are disadvantageous to any lighting unit. Too often the enclosing globe has been overlamped and placed too low, and this together with a dark or high ceiling has increased the contrasts so as to make them objectionable.

The modern diffusing glass enclosing globe, within which a lamp suited to the diameter of the globe in question has been properly centered, will give a well diffused illumination free from glare and objectionable shadows. Enclosing globes should be lamped according to the schedule in Table 8-1, the larger diameter given being preferable.

TABLE 8-1.—DIAMETER OF WHITE DIFFUSING ENCLOSING GLOBES

Size of lamp, watts	Globe diameter, inches	
	Minimum	Recommended
150	12	14
200	14	16
300	16	18

Neither is the allowable brightness of a lighting unit proportional to the brightness of its background. Nutting has shown[1] that if a source is of comfortable brightness against a background of 1 foot-lambert, a source against a 10 foot-lambert background must be not more than twice so bright to remain correspondingly comfortable. A contrast of 45:1 was found to be the limit for comfort where the brightness of the surroundings was 200 foot-lamberts. Curves plotted from these relations are shown in Fig. 8-1.[1]

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[1] NUTTING, *Trans. Illum. Eng. Soc.*, vol. 11, p. 943, 1916.

As an illustration of the preceding relations assume a room illuminated to 2 foot-candles obtained from four 1,500-lumen lamps in 10-in. enclosing globes, 9 ft. above the floor. To increase the illumination to 20 foot-candles would require 15,000 lumen lamps. Allowing a background 10 times as bright and permissible brightness of the source twice as great, would require a globe, some 22 in. in diameter to produce comfortable illumination.

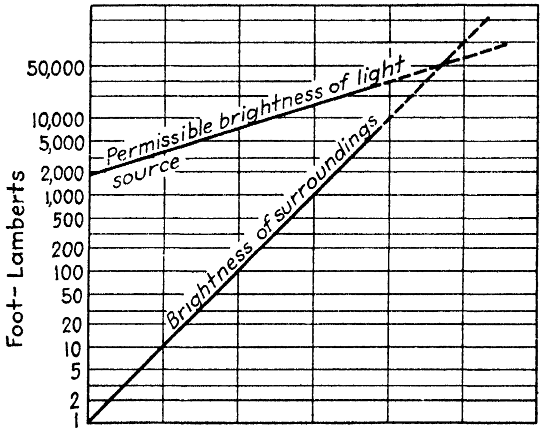

FIG. 8-1.—The relation between permissible brightness of light source and brightness of surroundings.

The semi-indirect lighting system while transmitting some 5 to 25 per cent of the light downward reflects more than half of the light from the source upward. Luminaires of good design should have a bowl of such density and diffusion that the brightness will not exceed 500 foot-lamberts. Semi-indirect illumination has the same general characteristics as indirect lighting. Illustrations 12 and 13 in Fig. 8-4 show the principle of this type of luminaire.

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[1] *Mag. of Light* (General Electric Company), vol. 5, p. 6, October, 1936.

Indirect Lighting System.—Indirect lighting is usually considered to be that system by which the source of light is entirely concealed from view and no light passes directly to the working plane. Effective lighting comes from the comparatively large area of the ceiling which becomes the secondary source of light. Because of the large area of this secondary source the quality of diffusion is excellent, the shadows are softened, and the eye is able to function with ease and with minimum of fatigue.

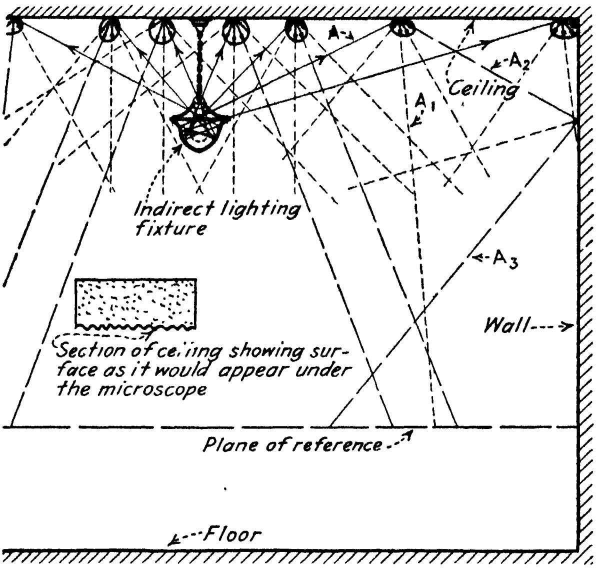
A
A₂
Ceiling
A₁
Indirect lighting fixture
A₃
Section of ceiling showing surface as it would appear under the microscope
Wall
Plane of reference
Floor

FIG. 8-2.—The principle of indirect lighting. The ceiling acts as a diffusing medium and breaks up each light beam into a series of rays, giving an illumination free from glare and strong shadows.

The principle underlying the diffuse quality of indirect illumination[1] is illustrated graphically in Fig. 8-2 which shows the method by which the light is reflected and re-reflected from the ceiling and walls of the room. The light beam "A" for example, strikes the ceiling and is broken up into rays and reflected in a number of directions. Some of the reflected rays, as for instance "A_1" go directly to the plane of reference, while others are reflected to the walls, where they are further broken up and reflected.

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[1] J. L. STAIR, *Trans. Illum. Eng. Soc.*, vol. 23, p. 53, 1928.

Thus it is that the illumination that reaches the reference plane is the combined effect of the multitude of reflected rays coming from many directions, each ray softening the shadows that might be cast by the others, and resulting in the diffuse daylight quality so characteristic of the indirect lighting system. Indirect lighting is not shadowless, as is sometimes supposed. The shadows are much softened but not eliminated. Furthermore, indirect lighting has a directional effect, contrary to the popular notion, as can be easily demonstrated.

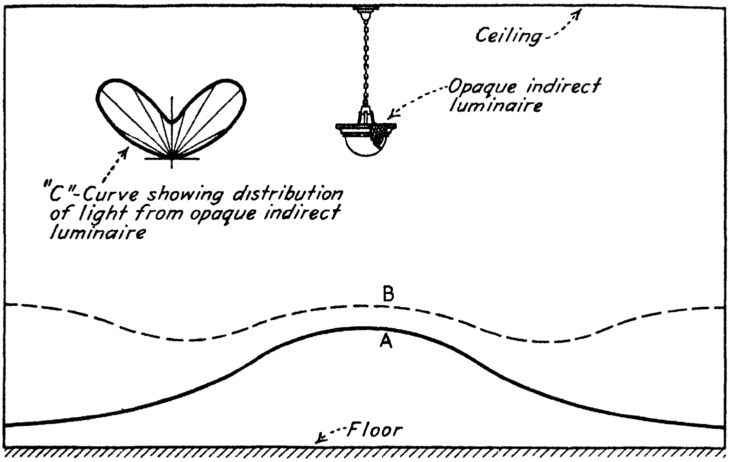
Ceiling
Opaque indirect luminaire
"C"-Curve showing distribution of light from opaque indirect luminaire
B
A
Floor

FIG. 8-3.—The above curves show the illumination delivered by indirect fixtures. The intensity of illumination does not fall off rapidly as one approaches the corners of the room. Curve *A* represents lighting values for one unit, and curve *B* is the result of two or three units when spaced 18 or 20 ft. apart.

The uniform values of illumination received in all parts of the room where this sytem is employed are suggested in Fig. 8-3.[1] Curve *A* represents the values from a single indirect luminaire. It will be noted that the highest value of illumination is directly under the unit. The intensity is represented by the vertical distance from the base line to a point on the curve. Curve *B* represents the combined effect of two or three units which, when the values are added, exhibit very uniform results. In large office spaces where each desk receives light from a number of units, the "uniformity curve" becomes essentially a straight line. Curve *C* illustrates the manner in which the light is distributed toward the ceiling by the standard type of indirect luminaire.

[1] J. L. STAIR, *Trans. Illum. Eng. Soc.*, vol. 23, p. 53, 1928.

Typical equipment for commercial indirect lighting in office spaces and drafting rooms consists primarily of pendant luminaires which are usually suspended from the ceiling. However, equipment for cove lighting from cornices, moldings, wall brackets and pedestals is frequently applied when the conditions are suitable. Pendant luminaires contain reflectors for either a single or a multiple number of lamps, and are supplied in metal or of composition material.

Another style known as the luminous indirect unit[1] has the opaque metal bowl replaced by one of glass, which conceals a reflector and a diffusing element. The purpose of the diffusing cup is to evenly illuminate the glass bowl to a pleasing brightness. In many locations the psychological value of the lighted bowl is desired. This type has the advantage that the indirect lighting quality is not sacrificed for the luminous effect. By properly proportioning the diffusing element, the brightness of the bowl may be controlled. Usually this value is less than 1½ candles per square inch.

A more recent type is the glass-topped indirect luminaire, available in either the luminous or opaque styles. This luminaire has all of the essential elements of the luminous unit just described, with the added feature of the glass covering. This particular style has been designed to deliver 90 per cent of the light upward and 10 per cent of the light downward through the hemispherical outer glass bowl.

Illustrations of types of direct, semidirect, semi-indirect, and indirect luminaires in portable, suspended, built-in and special forms together with their methods of application are shown on the following pages[2] in Figs. 8-4, 8-5, 8-6 and 8-7.

Location of Lamps.—The number of luminaires to light a room is determined by the maximum allowable spacing of the luminaires. This in turn is regulated by the height at which the luminaires are located above the working plane. The relation between height and spacing for reasonably uniform illumination is based upon the distribution of light from the lighting unit, as will be explained in a later chapter.

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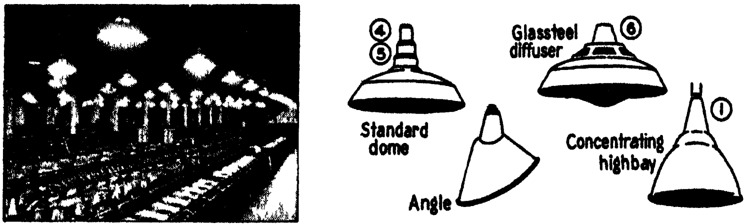
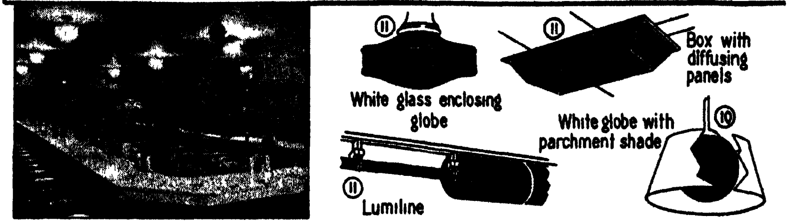
[1] *Ibid.*

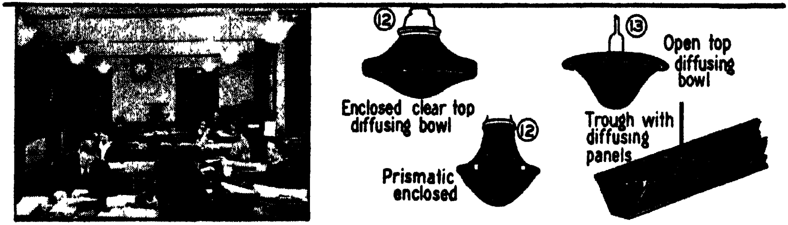
[2] WARD HARRISON and C. E. WEITZ, Illumination Design Data, LD-6A, Nela Park Eng. Dept., General Electric Company, 1936.



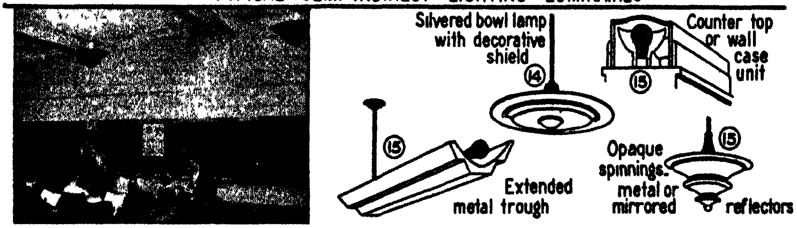
TYPICAL DIRECT LIGHTING LUMINAIRES


⑪
White glass enclosing globe
⑪
Box with diffusing panels
White globe with parchment shade
⑩
⑪
Lumiline

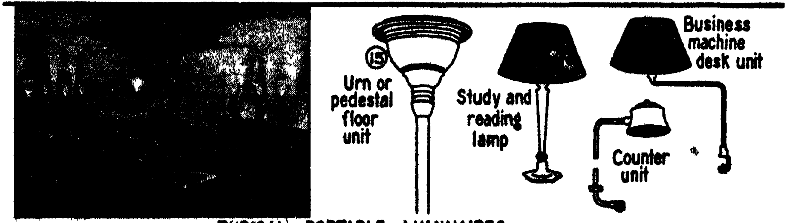
TYPICAL SEMI-DIRECT LIGHTING LUMINAIRES


⑫
Enclosed clear top diffusing bowl
⑬
Open top diffusing bowl
⑫
Prismatic enclosed
Trough with diffusing panels

TYPICAL SEMI-INDIRECT LIGHTING LUMINAIRES

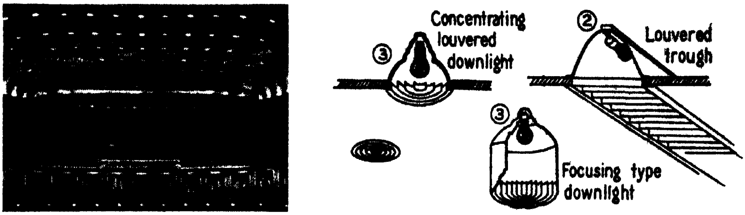

Silvered bowl lamp with decorative shield
⑭
Counter top or wall case unit
⑮
⑮
Extended metal trough
Opaque spinnings. metal or mirrored reflectors
⑮

TYPICAL INDIRECT LIGHTING LUMINAIRES

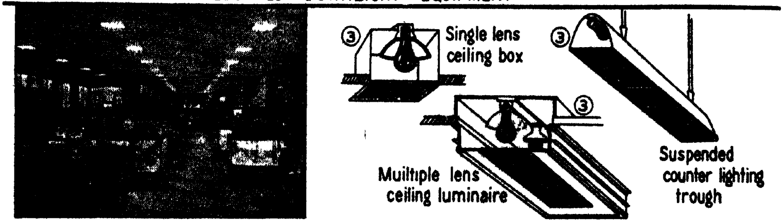


TYPICAL PORTABLE LUMINAIRES

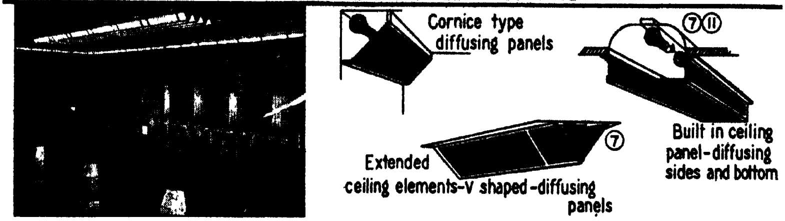
FIG. 8-4.—Suspended and portable lighting equipment.



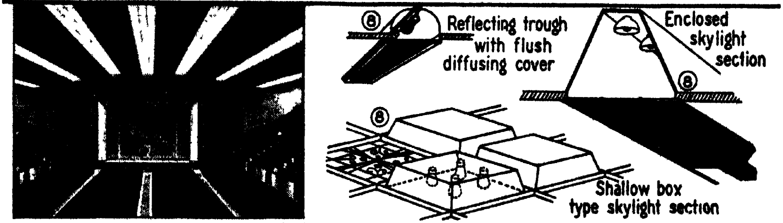
LOUVRED DOWNLIGHT EQUIPMENT


③
Single lens ceiling box
③
③
Muiltiple lens ceiling luminaire
Suspended counter lighting trough

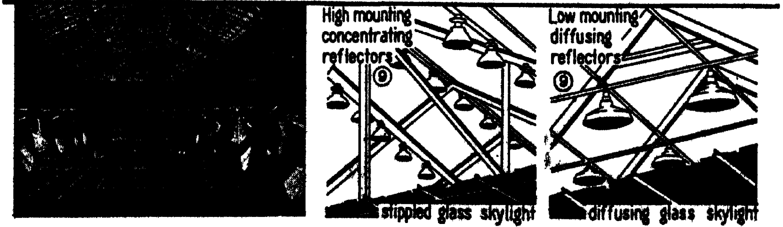
COMBINATION REFLECTOR-LENS CONTROL


Cornice type diffusing panels
⑦⑪
⑦
Extended ceiling elements-V shaped-diffusing panels
Built in ceiling panel-diffusing sides and bottom

PROJECTING TYPE DIFFUSING GLASS CEILING PANELS

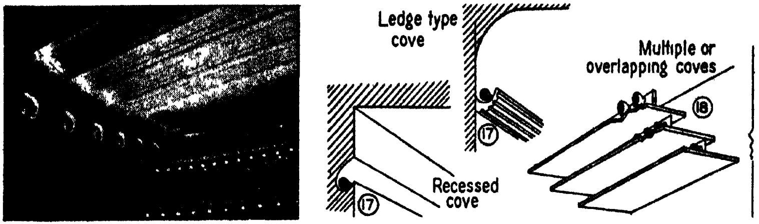

⑧
Reflecting trough with flush diffusing cover
Enclosed skylight section
⑧
⑧
Shallow box type skylight section

FLUSH TYPE PANELS OR SKYLIGHT SECTIONS

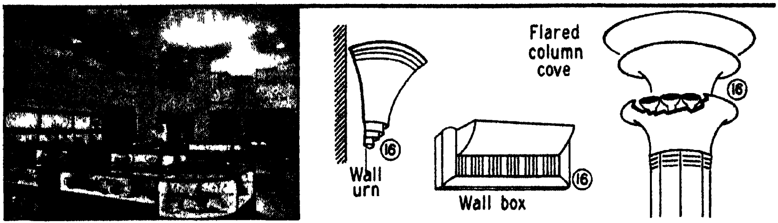

High mounting concentrating reflectors
⑨
Low mounting diffusing reflectors
⑨
stippled glass skylight
diffusing glass skylight

COMBINATION SKYLIGHTS-ARTIFICIAL AND NATURAL LIGHT

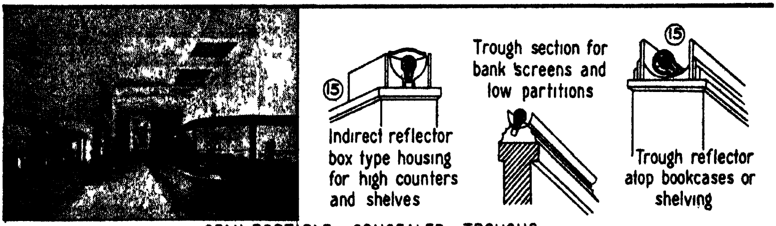
FIG. 8-5.—Built-in direct lighting methods.



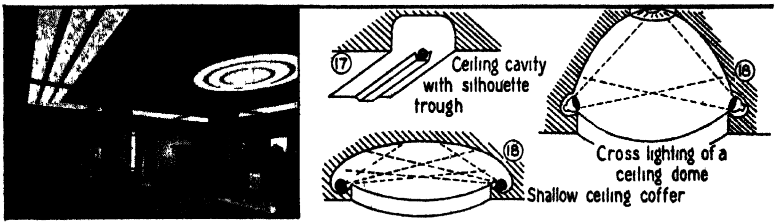
TYPICAL COVE SECTIONS



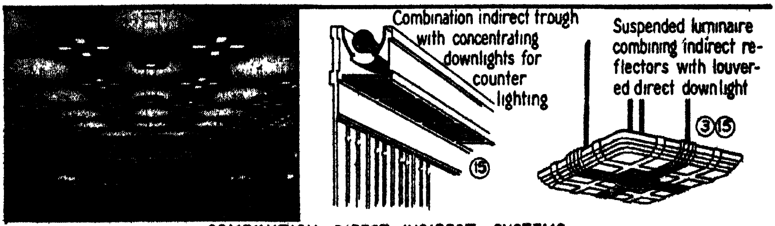
WALL URNS AND COLUMN COVES


⑮
Trough section for bank screens and low partitions
⑮
Indirect reflector box type housing for high counters and shelves
Trough reflector atop bookcases or shelving

SEMI-PORTABLE CONCEALED TROUGHS

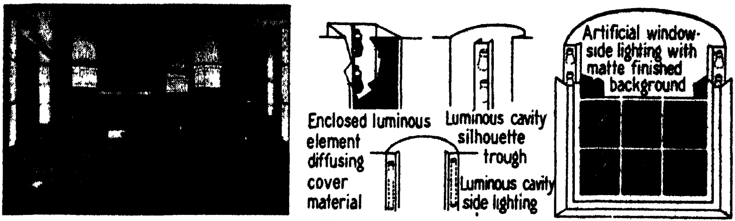

⑰
Ceiling cavity with silhouette trough
⑱
⑱
Cross lighting of a ceiling dome
Shallow ceiling coffer

CEILING CAVITY-COFFERS AND DOMES

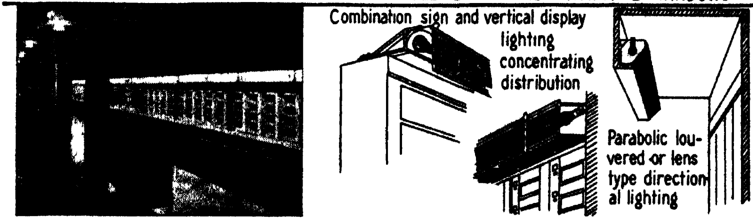

Combination indirect trough with concentrating downlights for counter lighting
Suspended luminaire combining indirect reflectors with louvered direct downlight
③⑮
⑮

COMBINATION DIRECT-INDIRECT SYSTEMS

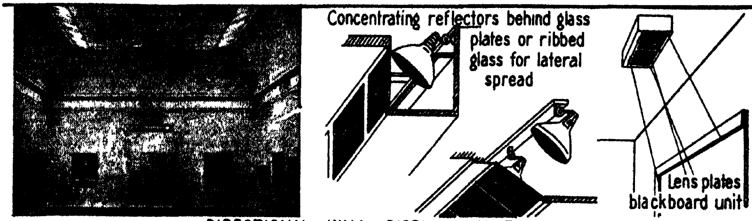
FIG. 8-6.—Built-in indirect lighting methods.


Enclosed luminous element diffusing cover material
Luminous cavity silhouette trough
Luminous cavity side lighting
Artificial window-side lighting with matte finished background

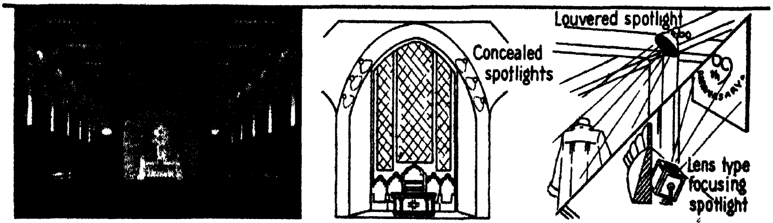
VERTICAL ELEMENTS AND ARTIFICIAL WINDOWS


Combination sign and vertical display lighting concentrating distribution
Parabolic louvered or lens type directional lighting

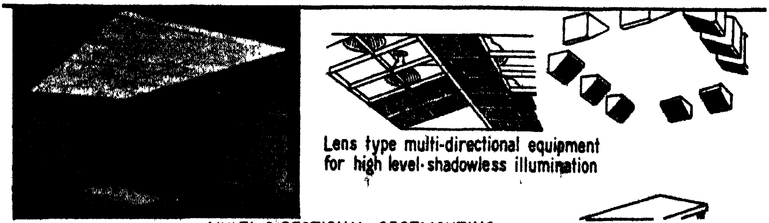
SHELVES-WALL CASES


Concentrating reflectors behind glass plates or ribbed glass for lateral spread
Lens plates blackboard unit

DIRECTIONAL WALL DISPLAY LIGHTING



FLOODLIGHTING AND SPOTLIGHTING


Lens type multi-directional equipment for high level-shadowless illumination

MULTI-DIRECTIONAL SPOTLIGHTING

Fig. 8-7.—Vertical elements—sidewall lighting—spotlighting.

Too great a spacing results in dark spaces on the working plane between lamps as shown in Fig 8-8 The remedy is shown in Fig. 8-9. The area receiving light from a unit having a certain light distribution will vary as the square of the height of the lamp above the reference plane To maintain the illumination the candle power of the lamp should vary also with the square of the height of suspension. Thus placing lamps near the ceiling or roof trusses, as the case may be, will permit the use of larger, more efficient lamps and require fewer outlets and luminaires. The height at which the units may be mounted clear of obstructions therefore dictates the maximum permissible spacing.

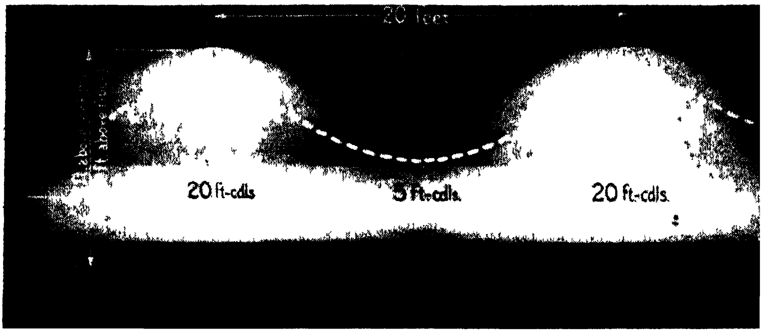


FIG 8-8 —Units spaced too far apart for their height furnish very uneven illumination, in this case a 4 to 1 variation and work positions midway between units will be inadequately lighted harsh shadows will also result The remedy is to mount the units higher, or if that is impossible to space them closer as shown in Fig 8-9

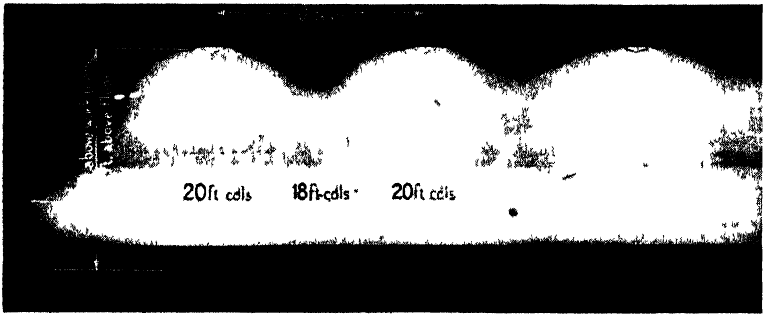


FIG 8-9.—It will be noted that if the permissible ratio between spacing and mounting height is not exceeded, uniform illumination will be produced. Note also the overlapping of light, which serves to eliminate shadows as the units are brought closer together

Contrary to the general belief, the absolute height in feet at which units are mounted has in itself no influence upon the percentage of light utilized, so long as the same proportions are maintained. For example if there are two buildings, one 20 × 50 ft. and 10 ft. in height, and the other 40 × 100 ft. and 20 ft. in height, it is clear from Fig. 8-10 that the effective angle and hence the efficiencies of the lighting systems in the two buildings will be the same. If the small building is illuminated by eight 100-watt lamps on 10-ft. centers and the large building by the same number of 400-watt lamps on 20-ft centers, the average intensity of illumination will be the same, neglecting the difference in the efficiency of the units, and its distribution will be similar. On the other hand, the *proportions* of a given building or room have an important bearing upon the percentage of light utilized. This is shown in Fig. 8-11, where much of the light is absorbed by the walls in a small room, whereas in a large room these light rays would be available on the working plane.

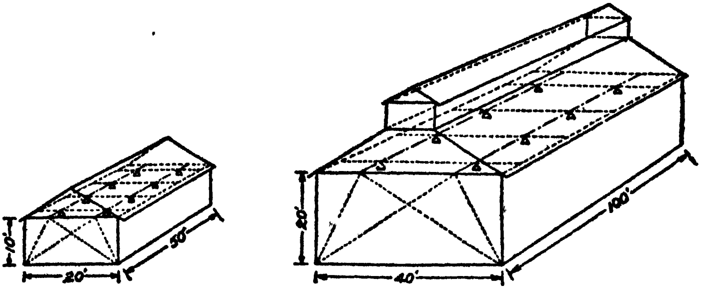


Fig. 8-10.—Illustration of effective angle.

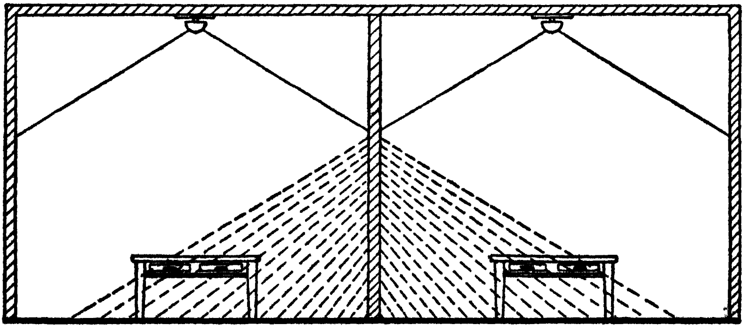


Fig. 8-11.—The coefficient of utilization is dependent upon room proportions. The light striking the partition is largely lost.

Spacing of Lighting Units.—The practice is to determine the style of lighting equipment best suited for the class of service and then, from a study of the conditions, surroundings, etc., calculate the number of lamps required by the methods taken up in Chap. IX. What is of concern now is the location of the lighting units—the height above the reference plane and the distance between the different units. It has become the practice, with suspended units, to divide the area of the room into as many equal rectangular sections as there are lamps required, making the sections as near squares as possible, and to place an outlet over the center of each section. If the room is of such dimensions that it can be divided into N equal squares, than the distance d between lamps located above the centers of the squares will be

$$d = \sqrt{\frac{S}{N}} \qquad (8\text{-}1)$$

where S = area of the room in square feet,
N = number of lamps or squares
d = distance between lamps in feet.

If the area must be divided into equal rectangles, having the dimensions b and c ft., and a lamp placed above the center of each rectangle, the $b = S/cN$ the distance between lamps in one direction and $c = S/bN$ the distance in the other direction.

Effect of Height of Suspension of Lamps upon Intensity of Illumination.—The fact that the intensity of illumination due to a point source of light varies inversely as the square of the distance between the source of light and the surface illuminated is familiar to everyone. But the significance and the practical application of the relationship existing between the distance from an infinite linear source or an infinite surface source and the intensity of illumination resulting therefrom are realized only by those most vitally interested in or intimately associated with the theory or uses of light.

It has been shown on page 186 that the illumination at a given point in a normal plane due to a tubular source of infinite length varies inversely as the distance from the source to the point illuminated and not inversely as the square of the distance, as with a point source. It is also well established that the illumination at a point on a normal plane due to an infinite surface source is quite independent of the distance between the point and the source (page 184).

It is obvious that luminous sources having infinite dimensions are merely theoretical, but it is interesting to assume certain practical conditions and learn how approximately the infinite-dimension relationship may apply in practice. For this purpose assume a 100-watt tungsten unit equipped with the intensive type of high-efficiency reflector. This type of reflector is so designed that, when used with the proper lamp and when the units are properly placed, approximately uniform illumination on the working plane will be obtained.

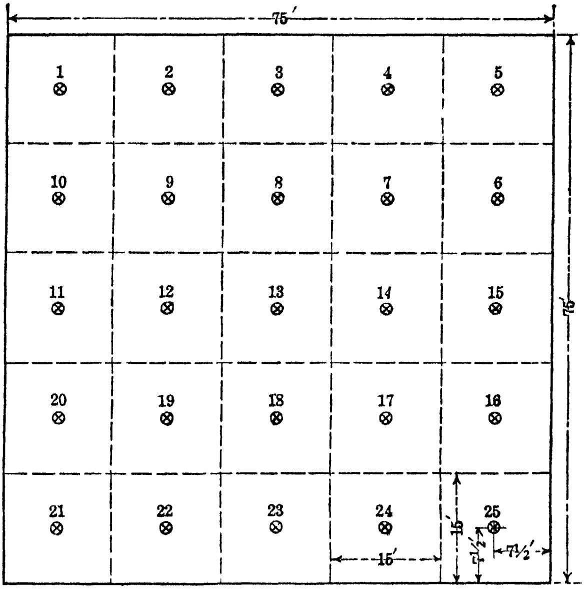


FIG. 8-12.—Location of 25 lamps in room 75 ft. square.

The distribution of light in a vertical plane through the axis of this type of lighting equipment is similar to curve $K = 1\frac{1}{4}$ in Fig. 9-6. The illumination due to one lamp placed 12 ft. above the reference plane is indicated by curve I_1, Fig. 9-7. If two lamps are placed 15 ft. apart and 12 ft. above the plane, the illumination along a line beneath the two lamps will be approximately uniform, as indicated by curve I_2, Fig. 9-7. With a distance of 15 ft. between lamps, 12 ft. is the minimum height of suspension which will secure approximately uniform illumination.

The two lamps can be placed at greater heights with the same spacing without impairing the uniformity of illumination, although the intensity of illumination will be lower.

To investigate the effect of the height of suspension of lamps above the plane illuminated, a room 75 × 75 ft. in size and lighted by the equipment just described has been assumed. The lamps are placed, according to common practice, at the centers of equal areas each 15 ft. square in this room. (Fig. 8-12.) The reflection from walls and ceiling is neglected, and the results are calculated from the polar curve by the point-by-point method employing the well-known equation

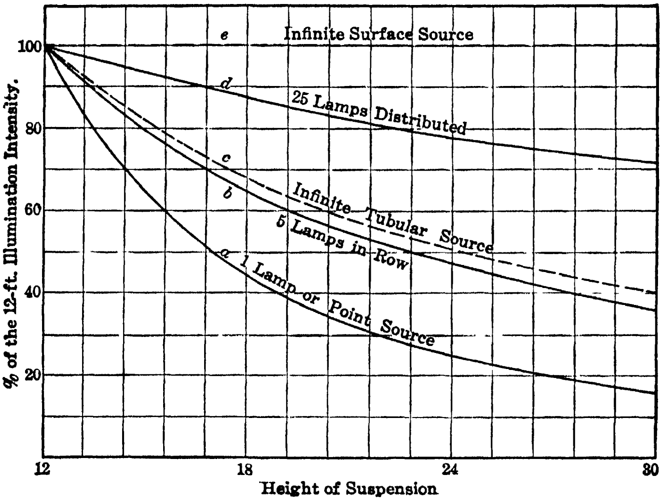


FIG. 8-13.—Effect of height upon the intensity of illumination.

$$E_h = \frac{I_a \cos^3 a}{h^2} \qquad (8\text{-}2)$$

where E_h = intensity of illumination on the reference plane

I_a = candle power a deg. from the vertical

h = height of lamps above the reference plane

The illumination at the center of the room was determined for: first, due to one lamp (No. 13), which may be considered a point source also; second, due to a row of lamps (Nos. 11 to 15, inclusive); and, third, due to all of the 25 lamps.

The results so calculated with the lamps at different heights are represented graphically in Fig. 8-13, together with those for the theoretical infinite linear and surface sources.

In interpreting these results it must be borne in mind that the lamps have been raised from 12 to 30 ft., or through a distance of 18 ft. in a room only 75 ft. square. Also no correction has been made for reflection from walls and ceiling. These curves, then, represent the maximum decrease that may be expected even with dark walls and ceiling. The decrease in intensity of illumination when the lamps are distributively located and are raised to a greater height is obviously due to a greater part of the light passing to the walls and ceiling. If the walls and ceiling are white, about 70 per cent of the light thus apparently lost will be returned to the reference plane and will greatly reduce the difference between curves *d* and *e*. The same line of reasoning will apply to some extent to the other cases as well. Moreover, a little thought will make it clear that, as the lamps are raised, the rays passing to the walls and the ceiling strike those surfaces at angles which are more effective in throwing this light onto the working plane.

Many mistakes are continually being made in the lighting of large rooms by locating the lamps too low. There appears to be an insistency among those "who know not, but think they know," that the proper height at which to locate the lamps of an installation is 10 or 12 ft. above the floor, irrespective of the size of the room, height of ceiling, class of service, or condition of the surroundings. In a large room with the lamps placed at this height, the sources of light are but little above the line of vision, and shine into the eyes when observing objects around the room. In this way the pupil of the eye is contracted and the illumination is less effective and less satisfactory than if its intensity be perhaps several per cent less but with the lamps placed higher and out of the range of vision.

Twilight Illumination.—It is generally recognized by illuminating engineers that the most critical test of a lighting system occurs when it is used to supplement natural illumination. An investigation by Prof. Hake[1] indicates that from 30 to 50 per cent greater intensity of artificial illumination may be necessary for satisfactory results during daylight periods than if the lighting is to be used only at night. As an explanation for this, it should be noted that the colors of natural and artificial light are not the same, and the resultant illumination is less than the arithmetical sum of the two. Also, by combining the two, a broader spectral distribution results, which may be expected to produce relatively lower visibility.

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[1] *Washington University Studies*, vol. 10, p. 113.

The 50 per cent increase mentioned above was found to be the average when type B Mazda lamps were used, while the 30 per cent increase referred to the type C lamp. Since the color of the light from the former differs more from daylight than does light from the latter, the results are as would be logically expected.

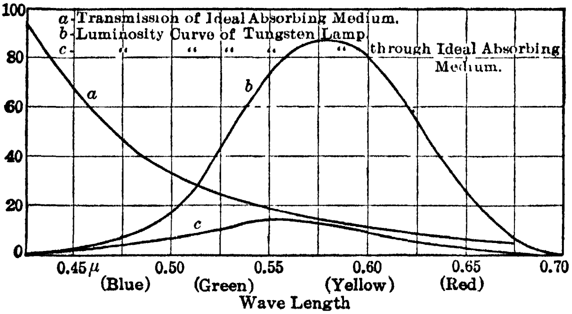

FIG. 8-14.—Transmission and luminosity curves for white light from a tungsten lamp.

That this greater required illumination is not due to the inability of the eye to adapt itself quickly to artificial light at the close of day is shown by drawing the shades and thereby excluding daylight. If the lighting system is satisfactory at night, it will be found satisfactory with drawn shades, although it may be inadequate before. This suggests the obvious fact that in many commercial installations where the windows are equipped with shades the mere lowering of these shades at twilight will often produce quite satisfactory results from an otherwise temporarily inadequate lighting system.

Artificial Daylight.—For the display of colored merchandise, the matching of colors, etc., a light of spectral composition similar to daylight should be used. Such a source may be secured by means of a filter which will absorb the excess in yellow and red rays of the tungsten lamp. The ideal screen should have perfect transmission at 0.42μ and a gradually increasing absorption toward the red end of the spectrum. The curves for such a unit are shown in Fig. 8-14[1] where curve *a* represents the transmission of an ideal absorbing medium and *c* the luminosity curve for the light from a tungsten lamp after passing through the ideal filter. It will be seen that the spectrum is continuous and thus suitable for color matching.

Glass filters have been designed for use with tungsten lamps to produce artificial daylight as for instance "Daylite" glass from the Corning Glass Works which has a transmission shown in Fig. 8-15. It will be noted that the shape of this curve is similar to curve *a* of Fig. 8-14.

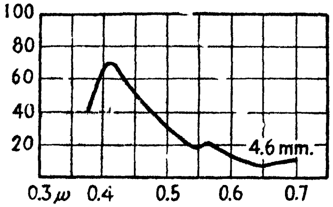

Fig. 8-15.—"Daylite" glass—graded long-wave absorption.

For practical purposes such a unit will be satisfactory. In fact it is suggested by Taylor[2] that any illuminant producing light having a color temperature between 5500 and 6500°K. and not departing appreciably from a black-body energy distribution may be considered satisfactory as a white light source.

We have three classes of light under which colors may be viewed, *viz.*, skylight, sunlight, and the light from incandescent lamps. If the matching of colors is critical and the goods are to be closely observed under these different illuminations, color matching may require more than a single unit for the purpose.

An equipment has been developed by Macbeth[3] in which three color-temperature ranges are available, 2000°K., 5000 to 6000°K., and 8000 to 10,000°K., which offers greater refinement. An intensity of several hundred foot-candles is made available in each color.

The assumption is that if two color samples match throughout this relatively wide range they will match anywhere, provided only that the observers have normal color vision. It will be noted that the above three ranges cover the illuminations from incandescent lamps, sunlight, and skylight.

Also it may be desirable to observe colors under artificial light resembling that under which it is to be used, as, for instance, an automobile which is usually seen in sunlight. Developments in glassware have made available lighting units emitting light simulating sunlight and north skylight. Tungsten lamps with reflectors and "noon sunlight" globes require three to four times the wattage taken by clear lamps in standard reflectors. When "north skylight" plates are used the wattage is six to eight times normal standard value.

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[1] Ives and Luckiesh, *Elec. World*, vol. 57, p. 1092, 1911.

[2] Taylor, *Trans. Illum. Eng. Soc.*, vol. 25, p. 154, 1930.

[3] *Trans. Illum. Eng. Soc.*, vol. 25, p. 154, 1930.

In the following paragraphs and illustrations (Figs. 8-16 to 8-21) are described and shown types of color-matching and color-modifying units now on the market. It will be noted that the high-pressure mercury lamp is used in the last two units.

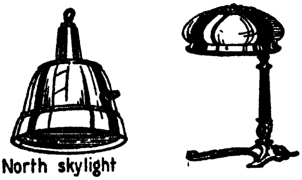

FIG. 8-16.

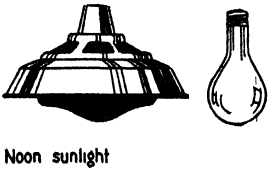

FIG. 8-17.

1. *North Skylight* (Fig. 8-16).—Equipments of this character employ accurately correcting filters by means of which it is possible to duplicate the color of outdoor daylight and are generally designed for localized lighting over counters in stores, for small areas, or special operations in industrial plants where precision in color identification, grading, and other color inspection is required. Illumination of the order of 100 foot-candles is desirable for this sort of work.

Color factories, paint and dye mixing, art studios, chemical analysis, dental mechanics, surgery, textile and cigar sorting and grading are examples of the application of skylight reproducing equipment.

As compared to unmodified artificial light, from 6 to 8 times the wattage is required for the same footcandle values.

2. *Noon Sunlight* (Fig. 8-17).—Enclosing globes of special crystal blue glass frosted on the inside modify the light from a lamp to approximate the color of direct sunlight at noon. Their applications are to some extent the same as skylight units, the actual choice depending on specific requirements. In general, noon sunlight equipment is used for less exacting color discrimination. For example, ink and dye mixing, and inspection may be done locally under skylight quality, and a general system of noon-sunlight equipment may be installed in certain rooms or over small areas restricted to manufacturing operations requiring clear color rendition, *e.g.*, as lithographing processes, color printing, tobacco grading, etc. Generally 100 or more foot-candles recommended.

As compared with unmodified artificial light, from two to three times the wattage is required for the same foot-candle values.

Artificial Daylight, Color-matching, and Color-modifying Equipment.[1]—The duplication of natural daylight is confined largely to those industrial and commercial applications involving accurate color discrimination or color rendition in varying degree, depending upon the specific requirements. Even in this field difficulties arise because the colorist has been accustomed, perhaps through years of habit, to a specific daylight quality peculiar to his location. It is practical and expedient, however,

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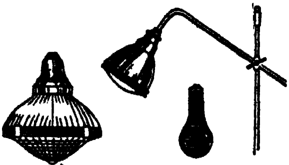
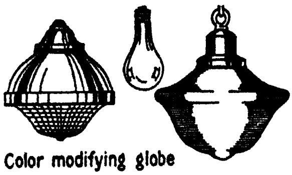
[1] HARRISON and WEITZ, *op. cit.*



'Daylight' lamps

FIG. 8-18.



Color modifying globe

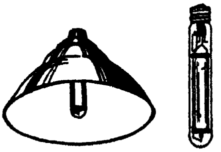
FIG. 8-19.

3. *Daylight Lamp* (Fig. 8-18).—Lamps with blue bulbs, commercially known as Mazda daylight lamps, emit a whiter light which is but a partial step toward daylight whiteness. In many instances of color rendition, their use gives sufficient color correction to be of considerable advantage over the warmer tones of unmodified light. The light blends well with natural daylight; in fact in many cases it is about the same color as the daylight that one gets indoors taking into account the prevalence of warm tones in window shades, walls and hangings; for this reason the use of daylight lamps in offices and many other places will be found to correct an unsatisfactory mixture of ordinary artificial light and inadequate daylight.

The next larger size of lamp will be required to produce approximately the foot-candle level as computed for a clear lamp of a given size. Daylight lamps can be used in all common types of equipment.

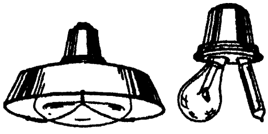
4. *Color-modifying Lamps* (Fig. 8-19).—Enclosing globes with slight bluish ingredient do not appreciably modify the color quality of illumination for utilitarian purposes, but have a considerable field of application by virtue of their whiter appearance. Such equipment corrects the yellowish tone usually noticeable with ordinary opal glassware. These usually give far less color correction than Mazda daylight lamps. The units are very pleasing, appear white and clean, and are often more satisfactory than units of yellowish tone, particularly when supplementing natural daylight. The spectral quality of illumination is usually not far from that of a clear bulb Mazda C lamp.

The illumination will be from 10 to 30 per cent less than for the same type of unmodified globe.



Mercury lamps

FIG. 8-20.



Combination-Mercury-Incandescent

FIG. 8-21.

5. *Mercury Lamps* (Fig. 8-20).—The line spectrum of mercury-vapor sources produces a characteristic color quality of light. It has a faint blue line, predominant yellow and green lines, with but a trace of red. The proportion of energy represented by each line varies slightly depending on the specific type of lamp. The source itself, or the light reflected from a white surface appears a bluish white but colored objects are much distorted in color appearance; blues become a purplish black, yellows and greens are emphasized, reds appear black. While colors cannot be reliably identified under mercury light, color contrast may be very pronounced. For that reason it may often be used as an auxiliary inspection source to reveal impurities and imperfections by introducing high color contrast that would not be apparent under white light.

6. *Combination Mercury-incandescent Lamps* (Fig. 8-21).—By combining mercury lamps lacking in red with incandescent lamps rich in red and orange, the resultant light is a very pleasing synthetic white light that seems cool and mixes well with natural daylight. There is still an excess of yellow and for that reason it is not a color-discriminating white because of the emphasis it gives yellow colors, but is very satisfactory for many industrial and commercial uses where accurate color discrimination of materials is not encountered. Combination low-pressure Cooper-Hewitt tubes and incandescent lamps offer a somewhat better color balance than combination of the new type H vapor sources with incandescent lamps, but the latter combination is more efficient.

In general equal lumens from incandescent and from mercury lamps are recommended for most applications of combination units.

to provide exact reproductions of daylight for any given requirement with the attendant advantage of constancy and 24-hr. availability.

Although color quality is accurately specified by color-temperature designations, equipments for reproducing daylight for working purposes may be grouped roughly into (1) skylight units, (2) sunlight units, and (3) units which provide a whiter light than the common types of general lighting equipment, but not so white as those discussed under 1 and 2 (Figs. 8-16, 8-17).

Production of Colored Light.—The light emitted by the incandescent lamp has a continuous spectrum. Hence since all colors are available in the unmodified light there is a fortunate condition for obtaining any effect.

Suppose red light is wanted—it is necessary to subtract the complementary color (blue-green). If blue-green light is wanted, the red, orange, and yellow rays are absorbed. If the effect of orange is to be obtained, the green, blue, and violet portion is screened out. To remove any of these rays is a comparatively simple matter. It is only necessary to pass the light through some medium which will absorb the particular part or parts which it is desired to remove.

To obtain the same illumination with colored light, many times the wattage must be used in comparison with that used for unmodified light. Table 8-2 gives some approximate figures on the absorption or loss of light necessary to obtain various colors to light from the incandescent lamp. These values are subject to considerable variation, depending on the purity of color secured and other factors.

TABLE 8-2

Ordinary designation	Absorption	Transmission	Wattage to produce same illumination as with unmodified light, per cent
Red	85 to 75	15 to 25	400 to 600
Orange	70 to 50	30 to 50	200 to 300
Yellow	40 to 20	60 to 80	125 to 150
Green	80 to 90	10 to 20	500 to 1,000
Blue	95 to 90	5 to 10	1,000 to 2,000
Purple	98 to 95	2 to 5	2,000 to 5,000

Fortunately, high level of colored lighting is rarely required.

Gelatin color screens are available in a wide variety of tints and shades. They are therefore, especially of service in producing delicate gradations of color. The gelatin material is rather difficult to manipulate, being affected by moisture and extreme heat or cold. The screens break easily and the life of the screen in service is rather short. Where used across the mouth of reflectors or in border and strip lights, special precautions must be taken to have a reliable holding device to prevent the gelatin from curling, opening a gap, and allowing unmodified light to escape, spoiling the effect. A network of fine wire overcomes this difficulty.

Colored Lighting.—In order to use colored lighting intelligently, a knowledge of certain comparatively simple fundamentals is necessary. It must be remembered that an object is seen by the light it reflects to the eye. A *pure* red light falling on a red object will be reflected in full color; falling on a green object it will be absorbed, and the object, reflecting no light, will appear black; falling on a yellow object, the object will appear red, because yellow reflects red among other colors.

It is rare, in practice, that pure colors are encountered, either in light or in pigments. The general effects are, however, of the order indicated.

The commercial reds (glasses, dips, and gelatin screens) are usually quite pure; the greens frequently contain blue, yellow, and even a trace of red. The blues are likely to contain all the colors, blue, of course, predominating. In practice, therefore, before making the actual installation it is desirable to experiment with both the colored light and the pigment intended for use on the scenery or decoration. By manipulation and correct choice of material, a desirable effect can be secured.

The action of colored light on colored material is of importance in decorative lighting and on the stage. By the proper combination of colored light and painted scenery, it is possible to change a scene entirely, without manipulating any scenery. This effect is based on the following principle:

If a red object on a white background is illuminated with red light, the background and the object will both reflect red light in its full value. There will be no contrast or difference in brightness, and the object will be invisible. Similarly, green light falling on a green object on a white background will cause the object to fade out.

Figure 8-22 shows, in a crude manner, the effect just discussed. In this illustration the foliage on the trees is green, the trunks and the branches are red. Illuminated with white light, the foliage will appear green and the limbs red. If it is illuminated with green light (or viewed through green spectacles), the foliage fades into the background and the bare branches appear black or a dark brown. If it is illuminated with red light, the foliage appears brownish and the limbs are practically invisible. This crude example is purposely simple, but with experimentation the principle can be extended to produce truly marvelous effects.

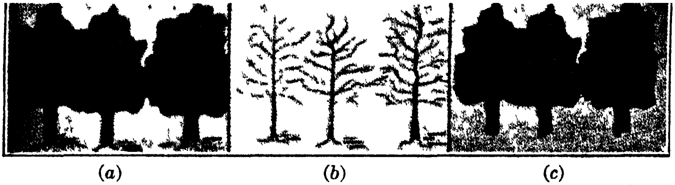


FIG. 8-22.—This illustrates, in a crude manner, the effect of colored light on colored objects. The foliage on the trees is green, the trunks and branches are red.

(a) The appearance when illuminated with white light.
(b) The appearance when illuminated with green light.
(c) The appearance when illuminated with red light.

An idea of the effect produced when colored light is thrown on objects of different colors can be obtained from Table 8-3.

Reflected Light.—The color of the light which reaches the working plane is in many cases quite different from that of the original illumination, owing to the selective reflection of surroundings. Daylight is altered considerably in spectral character by reflection from foliage, buildings, etc. Artificial light is altered in color by reflection from surroundings, *e.g.*, ceilings, walls, etc. The magnitude of the latter change is obviously dependent upon the relative amount of light flux which reaches the working plane indirectly as well as upon the color of the surroundings. It is reasonable to expect greater changes in indirect than in direct systems of lighting.

The results obtained in a miniature experimental room[1] are shown in Table 8-4 in terms of the color of the tungsten lamp.

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[1] *Trans. Illum. Eng. Soc.*, vol. 8, p. 61, 1913.

TABLE 8-3.—COLOR OF INCIDENT LIGHT RESULTS

Original color	Red light	Orange light	Yellow light	Green light	Blue light	Violet light
Black	Purplish black	Deep maroon	Olive-yellow	Greenish brown	Blue-black	Faint violet-black
White	Red	Orange	Light yellow	Green	Blue	Violet
Red	Intense red	Scarlet	Orange	Brown	Violet	Reddish violet
Orange	Orange-red	Intense orange	Yellow-orange	Faint greenish yellow	Violet-brown	Light red
Yellow	Orange	Yellow-orange	Orange-yellow	Yellowish green	Green	Brown, faintly red
Light green	Reddish gray	Yellow-green	Greenish yellow	Intense green	Blue-green	Light purple
Deep green	Reddish black	Rusty green	Yellowish green	Deep intense green	Greenish blue	Bluish gray
Light blue	Violet	Orange-gray	Yellowish green	Green-blue	Vivid blue	Violet-blue
Deep blue	Violet-purple	Orange-gray	Green-slate	Blue-green	Intense blue	Bright blue-violet
Indigo blue	Purple, slightly violet	Orange-maroon	Dull orange-yellow	Dull green	Dark indigo blue	Deep blue-violet
Violet	Purple	Red-maroon	Yellow-maroon	Bluish green-brown	Deep bluish violet	Deep violet

The results may readily be transformed from this basis into any form desired. The color analyses of the yellow and green papers are given for purposes of comparison. It is seen that, by reflection from colored surroundings, the color of the useful light is quite different from that of the original illuminant. With yellow walls and ceiling, for example, the useful light was much yellower than the light from a carbon incandescent lamp.

TABLE 8-4.—COLORIMETER MEASUREMENTS IN A MINIATURE ROOM UNDER VARIOUS CONDITIONS

	Red	Green	Blue
1. Tungsten lamp	33.3	33.3	33.3
2. Carbon lamp, 3.1 watts per candle	38.7	34.7	26.6
3. Carbon lamp, 4 watts per candle	43.0	33.7	23.3
4. Yellow walls and ceiling, indirect	53.1	37.0	9.9
5. Yellow walls and ceiling, direct	47.6	35.7	16.7
6. Yellow walls and white ceiling, indirect	43.2	35.5	21.3
7. Yellow walls and white ceiling, direct	42.1	35.3	27.6
8. Yellow paper	43.6	38.4	18.0
9. Green paper	34.5	39.8	25.7
10. Green ceiling and green walls, indirect	35.9	43.6	17.5
11. Green ceiling and green walls, direct	36.3	37.8	25.9
12. Green walls and yellow ceiling, indirect	48.2	42.6	9.2
13. Green walls and yellow ceiling, direct	39.8	39.6	20.6
14. Green walls and white ceiling, indirect	36.6	34.1	29.3
15. Green walls and white ceiling, direct	35.2	34.6	30.2

Figure 8-23 shows the relative percentages of the three components in the light remaining after various successive reflections from green paper. It is seen that the percentage of the green component in the reflected light rapidly increases with successive reflections, while the percentages of the other components decrease.

Maintenance.—A lighting system requires frequent inspection and cleaning. If it does not receive this attention, the illumination may become inadequate, and the engineer who designed the system is liable to be blamed and his judgment criticized. The depreciation of the lighting system may be *inherent* or *acquired.*

It is important to use lamps of the *proper voltage.* While initially the installation may be correct as to voltage, on replacing or ordering additional lamps an error may be made in specifying their voltage. Lamps are designed to operate at the voltage indicated on the label. This voltage rating takes into account renewal and energy costs. If the circuit voltage is appreciably higher than the label voltage, the result will be a short lamp life. If the voltage at the socket is considerably lower than that indicated on the label of the lamp in use, it will not emit the proper quantity of light. To make up for this loss of illumination, it would be necessary to install additional lamps. For instance, seven lamps operating at rated efficiency will give an amount of light equivalent to eight lamps operating 4 volts below the rated efficiency of the lamps. Before ordering lamps it is desirable to determine what average voltage is actually attained at the socket. Where the voltage of the system fluctuates during the day, or where it varies in different parts of the installation, it is proper to order lamps as near the average of this variation as possible.

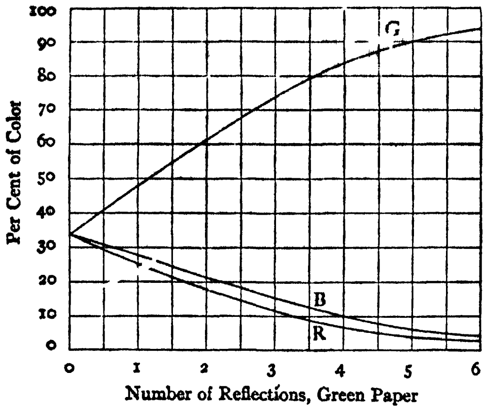

FIG. 8-23.—Effect of color of reflecting surface on color of reflected light.

As a tungsten lamp burns, small particles of tungsten are evaporated from the filament and collect on the lamp bulb in the form of a fine, dark deposit. Any accumulation on the interior surface of the bulb absorbs light, and blackened lamps should, of course, be replaced. It is comparatively simple to figure out the most economic point at which to replace lamps, taking into account the price of lamps and the cost of current.

Not only does a black deposit occur on the inside of the lamp bulb, but dust collects on the outer surface. This accumulation cuts down the light from the lamp and should be removed at the time reflectors are cleaned. This is often more serious than realized.

All lamps and reflectors should be regularly washed and cleaned. The period between cleanings will vary with locality and type of equipment. Obviously a steel, direct lighting reflector will not depreciate so rapidly as an indirect unit. The under surface of the reflector of the former offers very little opportunity for dust to gather, and that on the lamp bulb will be the primary cause of loss. With the inverted unit, however, a thin layer of dust soon settles on the entire reflecting surface, as well as on the lamp, which will reduce the light output appreciably in a very short time. Not only is this true, but the very arrangement of parts makes the accumulation greater. With the direct lighting equipment the reflector itself shields the lamp from falling particles, and they enter directly into the inverted unit.

Haphazard cleaning has not usually been found satisfactory, since the accumulation is so gradual that it is not readily noticed by those responsible. Much better success has been secured by systematic cleaning, at stated intervals, under the charge of a maintenance department where one person is absolutely responsible for this. As pointed out before, the periods between cleaning will vary with the locality and with the equipment. Considering average conditions and typical equipment, the fixtures in an office should be wiped out at least once every month, and removed for careful washing once every three or four months. In a foundry it is probably necessary to clean fixtures carefully once each week.

For cleaning dry dirt, wiping with a dry cloth or brush, then with a damp cloth, and finally drying all surfaces will prove satisfactory. Greasy or wet accumulations on any type of reflector must be removed by washing. Soap and water are good agents, but the film of soap must be removed by rinsing thoroughly, as dried soap accumulates dust rapidly. There are a number of cleaners on the market, but they should be carefully tested to see that they are so smooth as not to make microscopic scratches on the glass, and not leave a film of cleaning material.

The condition of *walls and ceilings* is very important. No matter how carefully painted a room may be, soot, smoke, and other agencies soon darken the surfaces of the room and cause it to lose considerable of its reflecting power. Any porous paint, such as calcimine or whitewash, is particularly susceptible to this effect. In industrial localities it is frequently necessary, if maximum economy of lighting is to be obtained, to paint the ceilings every year and a half and side walls every three years. A test to determine the reflection coefficient of the ceiling and walls at frequent intervals may save considerable on the lighting bill. In general, paint is far cheaper than electrical energy, and in dirty plants painting or cleaning is especially important.

Natural Illumination.—The variation of natural illumination in large rooms is shown in Figs. 8-24, 8-25, 8-26.

The curves of Fig. 8-24 illustrate the values of interior daylight illumination throughout a June day for a typical factory building in the latitude of New York City, the artificial illumination of which varied from 3 to 6 foot-candles. The ceiling, walls, and posts were white and the floor of light color.

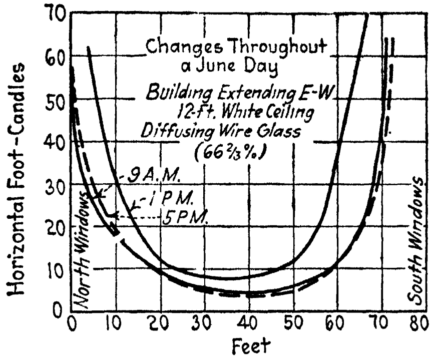

FIG. 8-24.—Daylight illumination across a building which extends from east to west.

For comparison, Fig. 8-25 shows similar data, but in a building extending in the north-south direction. Variations in foot-candles that result in too much light near the windows, and too little light at the center of the rooms, will be noted.

The lower daylight values prevailing on the upper floors of a building, as compared to those on the ground floor, are illustrated by Fig. 8-26. Where in positions more than 20 to 25 ft. from the windows, the natural daylight falls to 10 foot-candles or less, it should be possible to turn on general overhead electric lighting units to supplement the daylight. If, moreover, the windows be partially screened, the general lighting is improved in uniformity and some such results as depicted by the dotted curve of Fig. 8-26 are easily secured.

The usual criteria used in designing windows and rooms for daylighting, *viz.*, that the height to the top of the glass should not be less than half the depth of the room and that the glass area should be at least one-fifth of the floor area, are substantially reliable.

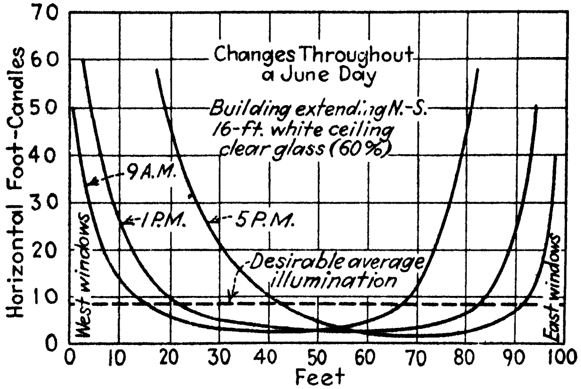

FIG. 8-25.—Daylight illumination across a building which extends north and south.

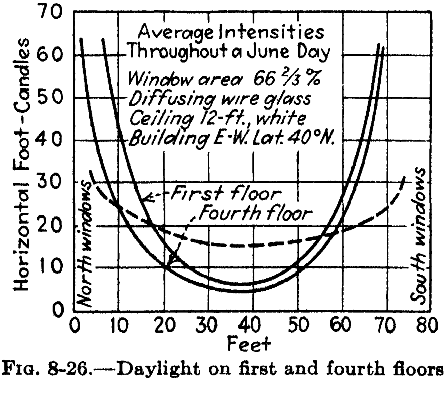

FIG. 8-26.—Daylight on first and fourth floors.

In all of the above examples of interior daylight illumination there is a rapid decrease in foot-candles as the distance from the windows increases. In order to obtain the maximum natural light in the interior of a building high windows of diffusing, prismatic, or ribbed glass may be used to advantage.

As a rule, it is better to confine the prismatic glass to the upper sash of a window, as its use in the lower sash is likely to cause glare; moreover it cuts off the outdoor view.

Natural Lighting.[1]—In planning a new factory building, the design should be such that the foot-candle values for daylight should be at least twice those found satisfactory for artificial light. The window openings should be so designed as to admit the greatest amount of light possible without producing glare and to render useful and valuable all parts of the floor space. In some cases the use of refracting or diffusing glass is desirable to redirect the light rays so as to improve the distribution of the daylight in the room, especially in the parts remote from the window.

The saw-tooth, monitor, or skylight windows of modern factory construction permit an adequate and more uniform daylight illumination of the entire area and are desirable when practicable.

If only one side wall contains windows, the width of the room should be less than twice the height of the top of the windows above the floor; if windows are in two parallel side walls, the width of the room between these walls should not exceed six times this window height. The monitor gives the best results when its width is about half the width of the building and the height of the windows in the monitor is one-half of the monitor width. The height of the windows in saw-tooth construction should be at least one-third of the span. In general, single-story industrial buildings should have a window area of at least 30 per cent of the floor area.

Reflection of daylight from surfaces outside a building has an important effect upon the lighting of an interior. Faces of structures, walls of courts, and roofs of saw-tooth buildings should be finished and maintained in the lightest practicable colors.

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CHAPTER IX

ILLUMINATION CALCULATIONS AND DESIGN

There are two basic methods of predetermining the illumination to be produced by a given lighting installation.

The first is known as the point-by-point method. It is based on the inverse-square law and involves the distribution of light or candle-power values of the lighting unit. It may be used for determining the illumination at specific points under conditions where only the direct light from the unit as indicated by its candle-power values reaches these points.

The second method, known as the flux-of-light method, offers a more convenient and reliable means of solving an illumination problem. It is based on the assumption that the relation of the amount of light flux producing illumination on the working plane to the total light flux radiated by the lamp has a certain value when used under similar conditions with respect to type of reflector, size of room, height of unit, reflection from ceiling and walls, etc.

The Point-by-point Method.—This method will be found useful in determining the values of illumination from and the location of special equipment used to produce a specific type of distribution of light, for the comparison of lighting units from the standpoint of efficiency and control of light and for the study of the street lighting luminaires as to their performance and merits.

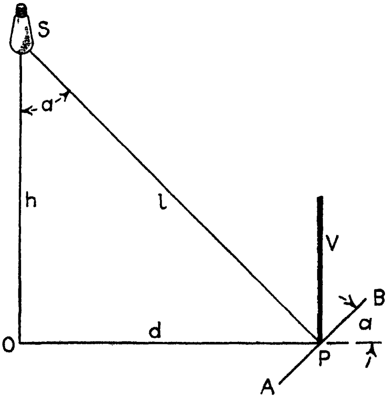

FIG. 9-1.—Diagrammatic representation of the relation of normal and horizontal illumination.

These calculations involve trigonometric equations, but sets of constants may be derived and tabulated so that results may be calculated by simple arithmetic. Assume the source of light to be located at a point S (Fig. 9-1) and let

I_a = candle power a deg. from the vertical
E_n = illumination on a normal surface
E_h = illumination on a horizontal surface
E_v = illumination on a vertical surface
d = horizontal distance from vertical through lamp to point whose illumination it is desired to ascertain
h = distance to lamp from horizontal plane
l = distance direct from source to point considered
a = the angle which light rays make with the vertical

Then the *illumination intensity at a point on a normal plane AB* will be

$$E_n = \frac{I_a}{l^2} = \frac{I_a}{h^2 + d^2} = I_a \frac{\cos^2 a}{h^2} \text{ foot-candles,} \qquad (9\text{-}1)$$

since

$$l = \frac{h}{\cos a} \qquad \text{or} \qquad l^2 = \frac{h^2}{\cos^2 a}. \qquad (9\text{-}2)$$

The *intensity of light on a horizontal plane OP* making an angle a with this normal plane will be $E_h = \frac{I_a \cos a}{l^2}$, and by substituting as before

$$E_h = I_a \frac{\cos a}{l^2} = I_a \frac{\cos a}{h^2 + d^2} = I_a \frac{\cos^3 a}{h^2} \text{ foot-candles} \qquad (9\text{-}3)$$

The horizontal distance d from the vertical may be found from the relation

$$d = h \tan a \qquad (9\text{-}4)$$

By the same reasoning the intensity of *illumination on a vertical plane PV* will be

$$E_v = I_a \frac{\sin a}{l^2} = I_a \frac{\sin a}{h^2 + d^2} = I_a \frac{\sin^3 a}{d^2} \text{ foot-candles} \qquad (9\text{-}5)$$

since

$$l = \frac{d}{\sin a} \qquad (9\text{-}6)$$

If it is desired to know the candle power which will furnish a certain illumination the foregoing equations may be transposed, giving

$$I_a = E_n l^2 = E_n(h^2 + d^2) = E_n \frac{h^2}{\cos^2 a} \qquad (9\text{-}7)$$

the *candle power required to illuminate a surface normal* to the rays,

$$I_a = E_h \frac{l^2}{\cos a} = E_h \frac{h^2 + d^2}{\cos a} = E_h \frac{h^2}{\cos^3 a} \qquad (9\text{-}8)$$

the *candle power necessary to give a horizontal illumination* E_h, and

$$I_a = E_v \frac{l^2}{\sin a} = E_v \frac{(h^2 + d^2)}{\sin a} = E_v \frac{d^2}{\sin^3 a} \qquad (9\text{-}9)$$

the *candle power sufficient to illuminate a vertical surface d* ft. from the source with an illumination of E_v foot-candles.

In Table 9-1 are given the values of sin α, cos α, tan α, $\sin^2 \alpha$, $\cos^2 \alpha$, $\sin^3 \alpha$, and $\cos^3 \alpha$, from 0 to 90 deg. The cosine and tangent values are for those values of α which increase from top to bottom, while the sine values are for those values of α increasing from the bottom toward the top.

Illumination on horizontal areas and the candle power to produce that illumination are the most common calculations in the distribution of light. In street lighting and in interior lighting where the lamps are equipped with opaque reflectors which throw the light downward on floors or surfaces dark in color, these equations are applicable and will give very approximate results. A set of constants per unit candle power for various heights of suspension of the source above the plane of reference may be tabulated, making preliminary determinations of such an installation comparatively simple. It will be seen that in the equation $E_h = I_a \frac{\cos^3 a}{h^2}$ the values of $\frac{\cos^3 a}{h^2}$ can be determined for various values of a and h, and designated by K; then $E_h = KI_a$ and $I_a = E_h/K$.

In Table 9-2 the values of $\frac{\cos^3 a}{h^2} = K$ are tabulated for heights from 4 to 30 ft. and for 0 to 50 ft. to the side.

This table can be extended by multiples of 10, the values of h and d being multiplied by 10 and the values of K divided by 100.

To make clear the manipulation of this table, the illumination on a horizontal surface 10 ft. below a luminous source and at a

TABLE 9-1

cos a	tan a	a	cos² a	cos³ a		cos a	tan a	a	cos² a	cos³ a	
1.00	.000	0	1.00	1.000	90	.694	1.04	46	.482	.335	44
.99985	.0175	1	.999	.999	89	.682	1.07	47	.465	.317	43
.9994	.0349	2	.998	.998	88	.669	1.11	48	.447	.299	42
.998	.0524	3	.997	.996	87	.656	1.15	49	.430	.282	41
.997	.0699	4	.995	.993	86	.643	1.19	50	.413	.265	40
.996	.0875	5	.992	.988	85	.629	1.23	51	.395	.249	39
.994	.105	6	.989	.983	84	.615	1.28	52	.379	.233	38
.992	.123	7	.985	.978	83	.602	1.33	53	.362	.218	37
.990	.1405	8	.981	.971	82	.588	1.38	54	.345	.203	36
.988	.1584	9	.975	.963	81	.573	1.43	55	.329	.189	35
.985	.176	10	.970	.955	80	.559	1.48	56	.312	.175	34
.982	.194	11	.963	.946	79	.544	1.54	57	.296	.161	33
.978	.212	12	.957	.936	78	.530	1.60	58	.280	.149	32
.974	.230	13	.949	.925	77	.515	1.66	59	.265	.137	31
.970	.249	14	.941	.913	76	.500	1.73	60	.250	.125	30
.966	.268	15	.933	.901	75	.485	1.80	61	.235	.113	29
.961	.287	16	.924	.888	74	.469	1.88	62	.220	.103	28
.956	.306	17	.914	.874	73	.454	1.96	63	.206	.0936	27
.951	.325	18	.904	.860	72	.438	2.05	64	.192	.0843	26
.945	.344	19	.894	.845	71	.423	2.14	65	.178	.0755	25
.939	.364	20	.883	.830	70	.407	2.25	66	.165	.0673	24
.933	.384	21	.872	.814	69	.391	2.35	67	.152	.0596	23
.927	.404	22	.859	.797	68	.375	2.47	68	.140	.0526	22
.920	.424	23	.847	.780	67	.358	2.60	69	.128	.0460	21
.913	.445	24	.834	.762	66	.342	2.75	70	.117	.0400	20
.906	.466	25	.821	.744	65	.325	2.90	71	.106	.0345	19
.899	.488	26	.808	.725	64	.309	3.08	72	.0955	.0295	18
.891	.509	27	.794	.707	63	.292	3.27	73	.0855	.0250	17
.882	.532	28	.779	.688	62	.275	3.48	74	.0759	.0209	16
.874	.554	29	.764	.669	61	.259	3.73	75	.0670	.0173	15
.866	.577	30	.750	.649	60	.242	4.01	76	.0586	.0142	14
.857	.601	31	.735	.630	59	.225	4.33	77	.0506	.0114	13
.848	.625	32	.719	.610	58	.208	4.70	78	.0432	.00899	12
.838	.649	33	.703	.590	57	.191	5.14	79	.0363	.00686	11
.829	.675	34	.687	.570	56	.173	5.67	80	.0301	.00520	10
.819	.700	35	.671	.550	55	.156	6.31	81	.0244	.00379	9
.809	.726	36	.655	.529	54	.139	7.11	82	.0193	.00268	8
.798	.753	37	.637	.509	53	.122	8.14	83	.0148	.00181	7
.788	.781	38	.621	.489	52	.1045	9.51	84	.0109	.00115	6
.777	.810	39	.604	.469	51	.0872	11.43	85	.00760	.000661	5
.766	.839	40	.587	.449	50	.0697	14.3	86	.00486	.000339	4
.754	.869	41	.569	.430	49	.0523	19.08	87	.00274	.000144	3
.743	.900	42	.552	.410	48	.0349	28.64	88	.00122	.0000425	2
.731	.932	43	.534	.391	47	.0174	57.29	89	.000306	.0000053	1
.719	.966	44	.517	.372	46	.00	∞	90	.0000	.0000	0
.707	1.00	45	.500	.353	45						
sin a			sin² a	sin³ a	a	sin a			sin² a	sin³ a	a

point 8 ft. to the side will be found. From the table it will be seen that for a height of 10 ft. and 8 ft. from the vertical K = 0.0048 and a = 39 deg. If the candle power of the source at

Table 9-2.—Intensity of Illumination in Foot-candles on Horizontal Plane at Points at Various Distances from a Light Source of 1 Candle Power

Height of light source above plane illuminated, in feet

Horizontal distance from point directly under light source to point where intensity of illumination is desired in feet.

d	4		5		6		7		8		9		10		12		14		16		18		20		25		30	
	a	K	a	K	a	K	a	K	a	K	a	K	a	K	a	K	a	K	a	K	a	K	a	K	a	K	a	K
0	0	.0625	0	.0400	0	.0278	0	.0204	0	.0156	0	.0124	0	.0100	0	.0069	0	.0051	0	.0039	0	.0031	0	.0025	0	.0016	0	.0011
1	14	.0571	11	.0377	9	.0267	9	.0198	9	.0153	6	.0121	6	.0099	5	.0069	5	.0051	4	.0039	3	.0031	3	.0025	2	.0016	2	.0011
2	27	.0447	22	.0321	18	.0237	16	.0181	14	.0143	12	.0115	11	.0094	9	.0067	9	.0050	7	.0038	6	.0030	6	.0025	5	.0016	4	.0011
3	37	.0320	31	.0252	27	.0199	23	.0158	21	.0128	18	.0105	17	.0088	14	.0063	12	.0048	11	.0037	9	.0030	9	.0024	7	.0015	5	.0011
4	45	.0221	39	.0190	34	.0160	30	.0134	27	.0112	24	.0094	22	.0080	18	.0059	16	.0045	14	.0036	13	.0029	11	.0024	9	.0015	8	.0011
5	51	.0152	45	.0141	40	.0126	36	.0110	32	.0095	29	.0083	27	.0072	23	.0054	20	.0043	17	.0034	16	.0028	14	.0023	11	.0005	9	.0011
6	56	.0106	50	.0105	45	.0098	41	.0089	37	.0080	34	.0071	31	.0063	27	.0050	23	.0040	21	.0032	18	.0026	17	.0022	13	.0015	11	.0011
7	60	.0076	54	.0079	49	.0077	45	.0072	41	.0067	38	.0061	35	.0055	30	.0045	27	.0037	24	.0030	21	.0025	19	.0021	15	.0014	13	.0010
8	63	.0056	58	.0060	53	.0060	49	.0058	45	.0052	42	.0052	39	.0048	34	.0040	30	.0033	27	.0028	24	.0023	22	.0020	18	.0014	15	.0010
9	66	.0042	61	.0046	56	.0047	52	.0047	48	.0046	45	.0045	42	.0041	37	.0036	33	.0030	29	.0026	27	.0022	24	.0019	19	.0014	16	.0010
10	68	.0032	63	.0036	59	.0038	55	.0039	51	.0038	48	.0037	45	.0035	40	.0032	36	.0028	32	.0024	29	.0021	27	.0018	22	.0013	18	.0009
11	70	.0025	66	.0028	61	.0031	58	.0032	54	.0032	51	.0031	48	.0031	42	.0028	38	.0025	35	.0022	31	.0019	29	.0017	23	.0013	19	.0009
12	71	.0020	67	.0023	63	.0025	60	.0026	56	.0027	53	.0027	50	.0026	45	.0025	41	.0022	37	.0020	34	.0018	31	.0016	25	.0012	21	.0009
13	73	.0016	69	.0019	66	.0021	62	.0022	58	.0023	55	.0023	52	.0023	47	.0022	43	.0020	39	.0018	36	.0017	33	.0015	28	.0012	24	.0009
14	74	.0013	70	.0015	67	.0017	63	.0018	60	.0019	57	.0020	54	.0020	49	.0019	45	.0018	41	.0017	38	.0015	35	.0014	30	.0011	25	.0008
15	75	.0011	72	.0013	68	.0014	65	.0015	62	.0016	59	.0017	56	.0017	51	.0017	47	.0016	43	.0015	40	.0014	37	.0013	31	.0010	27	.0008
16	76	.0009	73	.0011	69	.0012	66	.0013	63	.0014	61	.0015	58	.0015	53	.0015	49	.0015	45	.0014	42	.0013	39	.0012	32	.0010	28	.0008
17	77	.0008	74	.0009	71	.0010	68	.0011	65	.0012	62	.0013	60	.0013	55	.0013	50	.0013	46	.0013	43	.0012	40	.0011	34	.0010	29	.0007
18	77	.0006	74	.0008	72	.0009	69	.0010	66	.0011	63	.0011	61	.0012	57	.0012	52	.0012	48	.0012	45	.0011	42	.0010	36	.0009	31	.0007
19	78	.0006	75	.0007	72	.0008	70	.0008	67	.0009	65	.0010	62	.0010	58	.0011	53	.0011	50	.0011	46	.0010	44	.0010	37	.0009	32	.0006
20	79	.0005	76	.0006	73	.0007	71	.0007	68	.0008	66	.0009	63	.0009	59	.0009	55	.0010	51	.0010	48	.0009	45	.0009	39	.0008	34	.0006
25	81	.0002	79	.0003	77	.0004	74	.0004	72	.0004	70	.0005	68	.0005	64	.0006	61	.0006	57	.0006	54	.0006	51	.0006	45	.0006	40	.0005
30	82	.0001	81	.0001	79	.0002	77	.0002	75	.0003	73	.0003	72	.0003	68	.0004	65	.0004	62	.0004	59	.0004	56	.0004	50	.0004	45	.0004
35	....		83	.0001	80	.0002	79	.0002	77	.0002	76	.0002	74	.0002	71	.0003	68	.0003	65	.0003	63	.0003	60	.0003	54	.0003	49	.0003
40	....		....		81	.0001	80	.0001	79	.0001	77	.0001	76	.0001	73	.0002	71	.0002	68	.0002	66	.0002	63	.0002	58	.0002	53	.0002
50	....		....		....		82	.0001	81	.0001	80	.0001	79	.0001	77	.0001	74	.0001	72	.0001	70	.0001	68	.0001	63	.0001	59	.0001

39 deg. from the vertical is 200 candle power, then the horizontal illumination at a point 8 ft. from a vertical through the lamp will be

$$200 \times 0.0048 = 0.96 \text{ foot-candle.}$$

The candle power of the source in that direction necessary to give an illumination of 0.952 foot-candle at that point will be

$$\frac{0.96}{0.0048} = 200 \text{ candle power}$$

Theoretical Curves for Uniform Illumination.[1]—It is often desirable to know the distribution of light from a luminous source which will give an approximately uniform illumination.

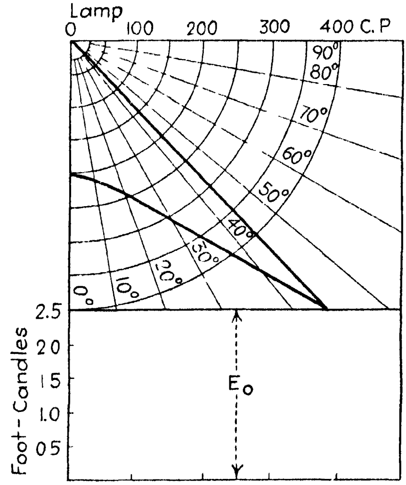

FIG. 9-2.—Distribution curve for uniform illumination by means of one source.

In order to obtain uniform illumination from one lamp, recourse is made to the expression $E_h = \frac{I_a}{h^2} \cos^3 a$, which is transposed into the form $I_a = \frac{E_h h^2}{\cos^3 a}$.

For uniform illumination E_h and h^2 will be constant and I_a at various values of a must vary inversely as $\cos^3 a$. A polar curve showing this relation is given in Fig. 9-2, which represents the distribution of candle-power intensity of a lamp in a vertical plane which will uniformly illuminate the area beneath it.

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[1] A. A. WOHLAUER, *Elec. World*, vol. 50, p. 1207, 1907.

For any given size of room and height of light center, the distribution curve which will give the desired distribution may be easily determined. It is obvious that any given distribution curve will give the same proportionate illumination so long as the relation between the size of the room and the height of the light center is kept constant.

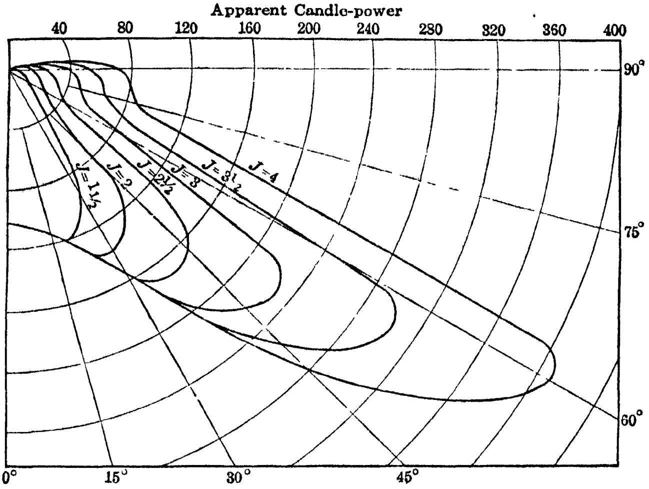

Fig. 9-3.—Curves for uniform illumination.

If now

$$J = \frac{\text{mean dimension of room}}{\text{height of light center above reference plane}}$$

then for any value of J there is a given distribution curve which will produce the desired distribution of illumination.

The curves of Fig. 9-3[1] have been derived to give uniform illumination over certain surfaces for different values of J from 1.5 to 4. Hence, for uniform illumination in a small room having one central luminaire, types of distribution similar to those shown in Fig. 9-3 are necessary. In practice, however, the diffusing glassware necessary to lower the intrinsic brightness of the source does not, in general, give distributions similar to these. The reflections from ceiling and walls tend toward greater uniformity and this light together with that from the ordinary luminaire usually gives an illumination sufficiently uniform for practical purposes. Obviously the area thus illuminated by one lamp is limited. In order, therefore, to illuminate larger areas uniformly, a number of lamps must be so arranged that the distribution of light will produce the desired effect. Obviously a number of lamps having a distribution of light similar to that shown in Fig. 9-2 would not suffice, since each lamp would uniformly illuminate a circular area as indicated in Fig. 9-4, and the areas between the circles shown shaded in the figure would receive no light.

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[1] Sweet, *Trans. Illum. Eng. Soc.*, vol. 4, p. 745, 1909.

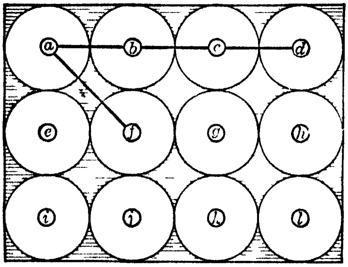

FIG. 9-4.—Sporadical uniform illumination.

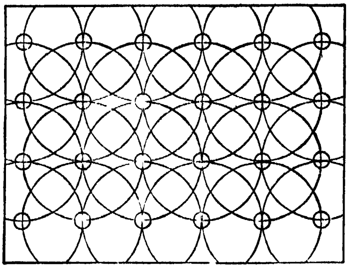

FIG. 9-5.—Uniform illumination by overlapping straight illumination curves.

It follows, then, that the polar candle-power distribution must be modified and the lamps so placed that the illumination from lamps will overlap. Such a condition is represented by Fig. 9-5, in which the small circles represent the location of the lamps and the large circles concentric with them represent the areas illuminated by the respective lamps.

Uniform illumination is a good criterion to work for, and with the distance between lamps established it follows that the *minimum* height of suspension above the reference plane will be determined by the distribution of light from the unit chosen.

Analyzing this phase of the subject, Sweet[1] derived a set of curves (Fig. 9-6) showing the different distributions for $d/h = K = \frac{1}{2}, \frac{3}{4}, 1, 1\frac{1}{4}, 1\frac{1}{2}$, and 2. In other words, for uniform

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[1] *Ibid.*

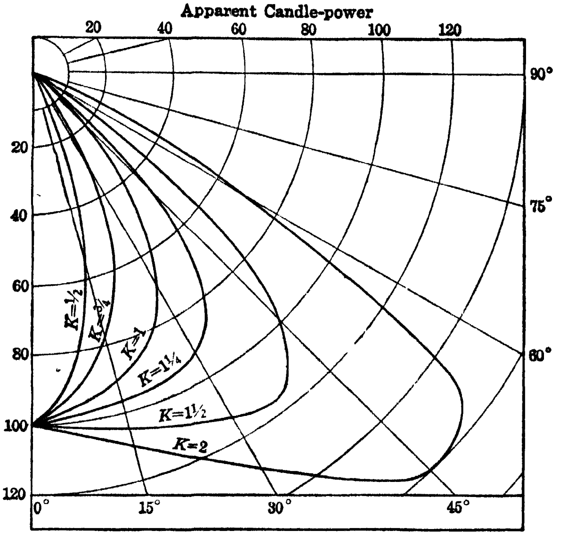

Fig. 9-6.—Curves to give uniform illumination. (Two or more lamps.)

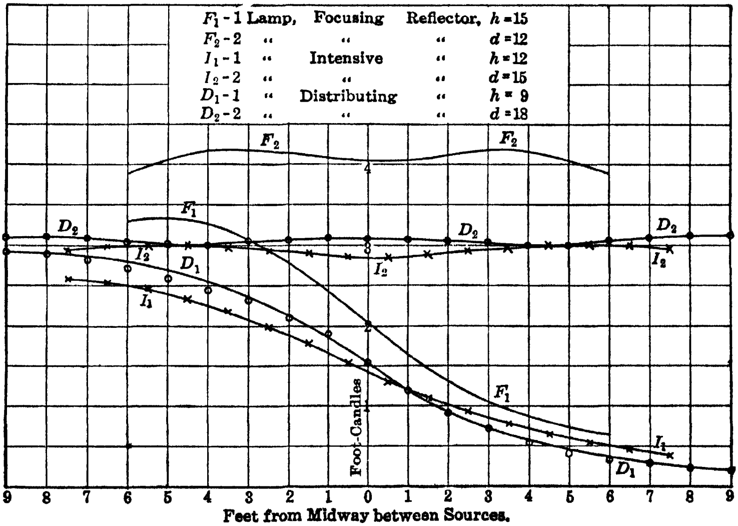

Fig. 9-7.—Illumination due to one and two 250-watt tungsten lamps equipped with intensive, extensive and focusing types of reflectors.

illumination the maximum distance between lamps must not be more than $\frac{1}{2}$, $\frac{3}{4}$, etc., of the height of suspension above the reference plane.

In Fig. 9-7 are shown the illumination curves for one and for two lamps in three different designs of reflectors. F refers to the focusing type of reflector used for high installations or for high intensity over a small area and producing a polar curve similar to $K = 0.8$ in Fig. 9-6. I refers to the intensive type used for general lighting purposes and having a distribution similar to $K = 1\frac{1}{4}$, and D the distributing or extensive type with a polar curve similar to $J = 2$ of Fig. 9-3. The illuminations produced by each of these units are shown by curves F_1, I_1, and D_1, respectively, of Fig. 9-7. Curves F_2, I_2, and D_2 show the resulting illumination from two units of each type when placed as indicated.

Flux-of-light Method.—While the point-by-point method of calculating illumination is fundamental, it will be found too cumbersome for general use. Neither does it take into account the light reflected from walls and ceiling, or other factors which may be present under various conditions.

The flux-of-light method is based on the assumption that, under similar conditions as to type of luminaire, color of walls and ceiling, size of room, etc., the lumens on the working plane will be a definite percentage of the total emitted by the lighting unit or units.

The lumens on the working plane will equal the average foot-candle intensity E_0 multiplied by the room area S in square feet. This value divided by the lumens per lamp F_t times the number of lamps N gives the percentage mentioned above and known as the *coefficient of utilization*, given in Table 9-7.

The coefficient of utilization obviously varies with the reflecting power of the ceiling and walls of a room and also with the size of the room. *Room index* for rooms of different proportions is given in Table 9-6.

Since lamps decrease in candle power during their life and the accumulation of dust and dirt further reduces the available light, the calculations must involve another factor M equal to the ratio of the average to the initial illumination or maintenance factor.

The flux-of-light method may be used to calculate the size of lamp, the number of lamps, or resulting illumination, as will be seen from the following.

$$\text{Lamp lumens outlet } (F_0) = \frac{\text{Foot-candles } E_0 \times \text{square feet per outlet } S}{\text{Coefficient of utilization } C \times \text{maintenance factor } M}$$

or

$$\text{Foot-candles } (E_0) = \frac{\text{Lamp lumens } F_t \times \text{coefficient of utilities } C \times \text{maintenance factor } M}{\text{Area per lamp in square feet } S_1}$$

Obviously these equations can be transposed and used to find any one of the above values having the others given or assumed. Thus

$$F_t = \frac{E_0 S}{NCM} \tag{9-10}$$

$$E_0 = \frac{F_t NCM}{S} \tag{9-11}$$

$$N = \frac{E_0 S}{F_t CM} \tag{9-12}$$

where F_t = total lumens per lamp when new (Table 9-3)
E_0 = average illumination, foot-candles (Tables 9-4, 9-5)
S = room area, square feet
N = number of lamps
C = coefficient of utilization (Tables 9-7, 10-3)
M = maintenance factor (Table 9-7)

In the following tables are given values for use in the flux-of-light calculations. In Table 9-3 are given the lumens emitted by new lamps at rated voltage F_t. In Tables 9-4 and 9-5 are foot-candle values that may serve as a guide for illumination intensities E_0. The room factors depending on the size of the room (known as the room index) are given in Table 9-6. Table 9-7 gives the utility coefficient C for examples of different types of luminaires for rooms of different sizes having different values of room index. This table also gives the maintenance factor M for the equipment.

TABLE 9-3.—LUMEN OUTPUT OF VARIOUS LAMP TYPES AND SIZES F_t*
Lumen outputs apply only to lamps burned at rated voltage

Watts	Lumens	Watts	Lumens
110–120-volt Mazda lamps		110–120-volt Mazda daylight lamps	
15	140	60	495
25	260	100	990
40	440	150	1,650
60	760	200	2,210
75	1,065	300	3,590
100	1,530	500	6,370
150	2,535		
200	3,400		
300	5,520		
500	9,800		
750	14,550		
1,000	20,700		
1,500	33,000		
Type H mercury lamps		220–240-volt Mazda lamps	
85	3,000	25	215
250	7,500	50	475
400	16,000	100	1,100
		200	2,920
		300	4,560
		500	8,350
		750	13,125
		1,000	19,000

* WARD HARRISON and C. E. WEITZ, Illumination Design Data, LD-6A, Nela Park Eng. Dept., General Electric Company, 1936.

Recommended Standards of Illumination E_0.—In the following table is presented the order of magnitude for intensities of illumination desirable for accurate and easy seeing. The letters *A*, *B*, and *C* refer to supplementary or specialized lighting discussed on pages 259, 268, 269, and 275.

High-intensity illumination for stores is desirable to facilitate seeing and to create an atmosphere which will draw customers and stimulate sales. It is a versatile and flexible medium for advertising and decoration and an important factor in meeting

TABLE 9-4.—COMMERCIAL AND PUBLIC INTERIORS*

A, *B*, and *C* refer to foot-candle ranges as explained on pages 269 and 275. These levels are usually, though not always, best obtained by supplementary or specialized lighting which may be accomplished by one or more of the methods referred to and discussed on pages 259, 268, 269, and 275.

	Foot-candles
Armories, drill sheds and exhibition halls	10
Art galleries:	
General	5
On paintings	*B*, Fig. 9-9*a*
Auditoriums	5
Automobile showrooms	20
Banks:	
Lobby	10
Cages	*B*, Fig. 9-9*e*
Offices	20
Barber shops, beauty parlors	20
Churches:	
Auditoriums	5
Sunday school rooms	10
Pulpit or rostrum	15
Club and lodge rooms:	
Lounge, reading rooms	20
Auditoriums	5
Courtrooms	10
Dance halls	5
Drafting rooms	30
Fire-engine houses:	
When alarm is turned in	10
At other times	2
Garages, automobile:	
Storage, Dead	2
Live	10
Repair and washing depts	*C*, Fig. 9-13*a*, *b*, *c*
Hangars, airplane	10
Repair, dept	*C*, Fig. 9-13*b*
Hospitals:	
Corridors	2
Laboratories	20
Lobby, reception room	5
Operating room	20
Operating table	*A*, Fig. 9-9*c*
Private rooms, wards (with local illumination)	20
Hotels:	
Lobby	10

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* WARD HARRISON and C. E. WEITZ, Illumination Design Data, LD-6A, Nela Park Eng. Dept., General Electric Company, 1936.

TABLE 9-4.—COMMERCIAL AND PUBLIC INTERIORS.—(*Continued*)

	Foot-candles
Dining room	5
Kitchen	10
Guest rooms	10
Corridors	2
Writing rooms	20
Libraries:	
Reading room	20
Stack room	10
Moving-picture theatres:	
During intermission	5
During pictures	0.1
Museums:	
General	10
Special displays	*B*, Fig. 9-9*b*
Night clubs, bars	5
Office buildings:	
Bookkeeping, typing, accounting	30
Business machines, power driven (transcribing, tabulating)—calculators, key punch, bookkeeping	*B*, Fig. 9-9*f*
Conference room:	
General meetings	10
Office activities (*see* Desk work)	
Corridors and stairways	5
Desk work:	
Intermittent reading, writing	20
Prolonged close work, computing, studying, designing, etc	30 to 50
Reading blueprints, plans	30
Drafting:	
Prolonged close work—art drafting, designing in detail	30 to 50
Rough drawing, sketching	30
Filing, index references	20
Mail sorting	20
Reception rooms	10
Stenographic work—Prolonged reading shorthand notes	30 to 50
Vault	10
Post Offices:	
Lobby	10
Sorting, mailing, etc	20
Storage	10
Offices, private and general	20

TABLE 9-4.—COMMERCIAL AND PUBLIC INTERIORS.—(*Continued*)

	Foot-candles
File room, vault	10
Corridors, stairways	2
Professional offices:	
Waiting rooms	10
Consultation rooms	20
Operating offices	20
Dental chairs	*C*, Fig. 9-9*d*
Restaurants, lunchrooms and cafeterias:	
Dining area	10
Food displays	*C*, Fig. 9-10*a*, *b*
Schools:	
Auditoriums	10
Classrooms, library, offices	20
Corridors, stairways	5
Drawing room	30 to 50
Gymnasium (basketball)	20
Laboratories	15
Manual training	20
Sewing room	*B*, Fig. 9-13*f*
Sightsaving classes	30 to 50
Study rooms—desks and blackboards	20
Service space:	
Corridors	5
Elevators, freight and passenger	10
Halls, stairways	5
Lobby	10
Storage	5
Toilets, washrooms	5
Telephone exchanges:	
Operating rooms	10
Terminal rooms	15
Cable vaults	5
Theatres:	
Auditoriums	5
Foyer	10
Lobby	15
Transportation:	
Cars:	
Baggage, day coach, dining, pullman	15
Mail:	
Bag racks, letter cases	20
Storage	5
Street railway, trolly bus, subway	15
Motor bus	10

TABLE 9-4.—INDUSTRIAL INTERIORS

	Foot-candles
Depots:	
Waiting rooms	10
Ticket Offices:	
General	10
Ticket rack and counters	*B*, Fig. 9-9*e*
Rest rooms, smoking rooms	10
Baggage checking office	15
Storage	5
Concourse	5
Platforms	2
Aisles, stairways, passageways	2
Assembly:	
Rough	10
Medium	20
Fine	*B*, Fig. 9-13*h*
Extra fine	*A*, Fig. 9-13*h*
Automobile manufacturing:	
Assembly line	*B*, Fig. 9-13*d*
Frame assembly	15
Body manufacturing:	
Assembly	20
Finishing, inspecting	*A*, Fig. 9-13*d*
Bakeries	20
Bookbinding:	
Folding, assembling, pasting, etc	10
Cutting, punching, stitching	20
Embossing	20
Breweries:	
Brew house	5
Boiling, keg washing, filling	10
Bottling	15
Candy making	20
Canning, preserving	20
Chemical works:	
Hand furnaces, boiling tanks, stationary driers, stationary and gravity crystallizers	5
Mechanical furnaces, generators, stills, mechanical driers, evaporators, filtration, mechanical crystallizers, bleaching tanks for cooking, extractors, percolators	10
Nitrators, electrolytic cells	15
Clay products, cements:	
Grinding, filter presses, kiln rooms	5
Molding, pressing, cleaning and trimming	10

TABLE 9-4.—INDUSTRIAL INTERIORS.—(*Continued*)

	Foot-candles
Enameling	15
Coloring, glazing	20
Cloth products:	
Cutting, inspecting, sewing:	
Light goods	20
Dark goods	*A*, Fig. 9-13*e*, *f*
Pressing, cloth treating (oilcloth, etc.):	
Light goods	10
Dark goods	20
Coal breaking, washing, screening	5
Construction, indoor general	10
Dairy products	20
Elevators, freight and passenger	10
Engraving	*A*, Fig. 9-13*j*
Forge shops and welding	10
Foundries:	
Charging floor, tumbling, cleaning, pouring and shaking out	5
Rough molding, core making	10
Fine molding, core making	20
Garages, automobiles:	
Storage:	
Live	10
Dead	2
Repair dept., washing	*C*, Fig. 9-13*a*, *b*, *c*
Glassworks:	
Mix and furnace rooms, pressing and lehr, glass-blowing machines	10
Grinding, cutting glass to size, silvering	20
Fine grinding, polishing, beveling, etching, decorating	*C*, Fig. 9-13 *l*, *m*, *n*
Inspection	*B*, Fig. 9-13 *k*, *m*, *n*
Glove manufacturing:	
Light goods:	
Cutting, pressing, knitting, sorting	10
Stitching, trimming, inspecting	20
Dark goods:	
Cutting, pressing, knitting, sorting	20
Stitching, trimming, inspecting	*A*, Fig. 9-13*e*, *f*
Hangars, airplane:	
Storage, live	10
Repair depts	*C*, Fig. 9-13*b*
Hat manufacturing:	

TABLE 9-4.—INDUSTRIAL INTERIORS.—(*Continued*)

	Foot-candles
Dyeing, stiffening, braiding, cleaning, refining:	
Light	10
Dark	20
Forming, sizing, pouncing, flanging, finishing and ironing:	
Light	15
Dark	30
Sewing:	
Light	20
Dark	*A*, Fig. 9-13*f*
Ice making, engine and compressor room	10
Inspection:	
Rough	10
Medium	20
Fine	*B*, Fig. 9-13*h–n*
Extra fine	*A*, Fig. 9-13*h–n*
Jewelry, watch manufacturing	*A*, Fig. 9-13*j*
Laundries, dry cleaning	20
Leather manufacturing:	
Vats	5
Cleaning, tanning, stretching	10
Cutting, fleshing, stuffing	15
Finishing, scarfing	20
Leather working:	
Pressing, winding, glazing:	
Light	10
Dark	20
Grading, matching, cutting, scarfing, sewing:	
Light	20
Dark	*A*, Fig. 9-13*f*
Locker rooms	5
Machine shops:	
Rough bench- machine work	10
Medium bench- machine work, ordinary automatic machines, rough grinding, medium buffing and polishing	20
Fine bench and machine work, fine automatic machines, medium grinding, fine buffing and polishing	*B*, Fig. 9-13*k*
Extra fine bench- machine work, grinding, fine work	*A*, Fig. 9-13*k*
Meat packing:	
Slaughtering	10
Cleaning, cutting, cooking, grinding, canning, packing	20

TABLE 9-4.—INDUSTRIAL INTERIORS.—(*Continued*)

	Foot-candles
Milling grain foods:	
Cleaning, grinding, rolling	10
Baking or roasting	20
Flour grading	30
Offices (*see* Office Buildings, page 248):	
Private and general:	
No close work	10
Close work	20
Drafting rooms	30
Packing, boxing	10
Paint manufacturing	10
Paint shops:	
Dipping, spraying, firing, rubbing, ordinary hand painting and finishing	20
Fine hand painting and finishing	*B*, Fig. 9-13*g*
Extra fine hand painting and finishing (automobile bodies, piano cases, etc.)	*A*, Fig. 9-13*g*
Paper box manufacturing:	
Light	10
Dark	20
Storage of stock	5
Paper manufacturing:	
Beaters, grinding, calendering	10
Finishing, cutting, trimming	20
Plating	10
Polishing, burnishing	15
Power plants, engine rooms, boilers:	
Boilers, coal and ash handling, storage-battery rooms	5
Auxiliary equipment, oil switches, transformers	10
Switchboards, engines, generators, blowers, compressors	15
Printing Industry:	
Matrixing and casting	10
Miscellaneous machines	15
Presses and electrotyping	20
Lithographing	*B*, Fig. 9-13*j*
Linotype, monotype, typesetting, imposing stone, engraving	*B*, Fig. 9-13*f*,*j*
Proofreading	*B*, Fig. 9-9*f*
Receiving and shipping	10
Rubber manufacturing, products:	
Calenders, compounding mills, fabric preparation, stock cutting, tubing machines, solid-tire operations, mechanical-goods building, vulcanizing	10

TABLE 9-4.—INDUSTRIAL INTERIORS.—(*Continued*)

	Foot-candles
Bead building, pneumatic-tire building and finishing, inner tube operation, mechanical goods trimming, treading	20
Sheet-metal works:	
Miscellaneous machines, ordinary benchwork	15
Punches, presses, shears, stamps, welders, spinning, medium benchwork	20
Tin plate inspection	*C*, Fig. 9-13*j*
Shoe manufacturing:	
Hand turning, miscellaneous bench and machine work	10
Inspecting, sorting raw material, cutting, stitching:	
Light	20
Dark	*A*, Fig. 9-13*f*
Lasting, welting	20
Soap manufacturing:	
Kettle houses, cutting, soap chip and powder	10
Stamping, wrapping and packing, filling packing soap powder	20
Steel and iron mills, bar, sheet, wire products:	
Soaking pits and reheating furnaces	5
Charging and casting floors	10
Muck and heavy rolling, shearing (rough by gauge) pickling and cleaning	10
Plate inspection, chipping	*C*, Fig. 9-13*j*
Automatic machines, light and cold rolling, wire drawing, shearing (fine by line)	15
Stone crushing and screening:	
Belt conveyer tubes, main-line shafting spaces, chute rooms, inside of bins	5
Primary breaker room, auxiliary breakers under bins	5
Screens	10
Storage-battery manufacturing, molding of grids	10
Store and stock rooms:	
Rough bulky material	2
Medium or fine material requiring care	10
Structural-steel fabrication	10
Sugar grading	30
Testing:	
Rough	10
Fine	20
Extra fine instruments, scales, etc	*A*, Fig. 9-13*h*
Textile mills:	
Cotton:	
Opening and lapping, carding, drawing, roving, dyeing	10

Table 9-4.—Industrial Interiors.—(*Continued*)

	Foot-candles
Spooling, spinning, drawing, warping, weaving, quilling, inspecting, knitting, slashing (over beam end)	20
Silk:	
Winding, throwing, dyeing	15
Quilling, warping, weaving, finishing:	
Light goods	15
Dark goods	30
Woolen:	
Carding, picking, washing, combing	10
Twisting, dyeing	10
Drawing-in, warping:	
Light goods	15
Dark goods	30
Weaving:	
Light goods	15
Dark goods	30
Knitting machines	20
Tobacco products:	
Drying, stripping general	10
Grading, sorting	*A*, Fig. 8-16
Toilets and washrooms	5
Upholstering, automobile, coach, furniture	20
Warehouse	5
Woodworking:	
Rough sawing, benchwork	10
Sizing, planing, rough sanding, medium machine and benchwork, gluing, veneering, cooperage	20
Fine machine and benchwork, fine sanding and finishing	30

competition. The order of magnitude is suggested in Table 9-5. Local lighting practice for show cases, show windows, and special displays are illustrated in Fig. 9-10 *a* to *j*.

Utilization Efficiency of Various Types of Equipment.[1]—The infinite variety of equipment with slight differences in output, distribution, and with various adjustment and control accessories presents almost endless combinations which affect the actual utilization. However, the 18 classifications for which coefficients of utilization have been computed present a wide diversity of conditions from direct to indirect, and the range is adequate for usual practical calculation requirements.

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[1] Harrison and Weitz, *op. cit.*

Detailed analysis and comparison of specific reflecting equipments can be made accurately only by a study of their actual distribution curves, from which specific coefficients of utilization can be derived. The use of Table 9-7 imposes the necessity of knowing approximately the output efficiency and distribution characteristics of the reflecting equipment under consideration in order to select the group to which it most nearly applies.

TABLE 9-5.—FOOT-CANDLE VALUES REPRESENTING ORDER OF MAGNITUDE RATHER THAN EXACT LEVELS OF ILLUMINATION FOR STORES*

	General interior lighting	Show-case	Special displays inside store			Show window	Lighting to reduce daylight window reflections
			Light colored	medium colored	Dark colored		
Large cities:							
Brightly lighted district	20	50 to 100	30 to 50	50 to 100	100 or more	200	200 to 1000
Secondary business locations	20	50 to 100	30 to 50	50 to 100	100 or more	100	200 to 1000
Neighborhood stores	15	50 to 100	30 to 50	50 to 100	100 or more	50	200 to 1000
Medium cities:							
Brightly lighted districts	20	50 to 100	30 to 50	50 to 100	100 or more	100	200 to 1000
Neighborhood stores	15	50 to 100	30 to 50	50 to 100	100 or more	50	200 to 1000
Small cities and towns	15	50 to 100	30 to 50	50 to 100	100 or more	50	200 to 1000

* WARD HARRISON and C. E. WEITZ, Illumination Design Data, LD-6A, Nela Park Eng. Dept., General Electric Company, 1936.

Computed Illumination Values.—The values of illumination in foot-candles for different-sized lamps and areas in Table 9-8 are calculated from Eq. 9-11, $E_0 = \frac{F_t N C M}{S}$. A maintenance factor of 0.70 is assumed.

Spacing and Mounting Height of Luminaires.[1]—The ceiling height, or rather the height at which units may be mounted clear of obstructions, limits the maximum permissible spacing.

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[1] HARRISON and WEITZ, *op. cit.*

Table 9-6.—Room Index*

Rooms classified according to their proportions

		Ceiling height, feet										
For semi-indirect and indirect lighting		9 and 9½	10 to 11½	12 to 13½	14 to 16½	17 to 20	21 to 24	25 to 30	31 to 36	37 to 50		
		Mounting height above floor, feet										
For direct and semi-direct lighting		7 and 7½	8 and 8½	9 and 9½	10 to 11½	12 to 13½	14 to 16½	17 to 20	21 to 24	25 to 30	31 to 36	37 to 50
Room width, feet	Room length, feet	Room index										
9 (8½ to 9)	8 to 10	H	I	J	J							
	10 to 14	H	I	I	J							
	14 to 20	G	H	I	J	J						
	20 to 30	G	G	H	I	J	J					
	30 to 42	F	G	H	I	J	J	J				
	42 up	E	F	G	H	I	J	J				
10 (9½ to 10½)	10 to 14	G	H	I	J	J						
	14 to 20	G	H	I	J	J	J					
	20 to 30	F	G	H	I	J	J					
	30 to 42	F	G	G	H	I	J	J				
	42 to 60	E	F	G	H	I	J	J				
	60 up	E	F	F	H	H	I	J				
12 (11 to 12½)	10 to 14	G	H	I	I	J	J					
	14 to 20	F	G	H	I	J	J					
	20 to 30	F	G	G	H	I	J	J				
	30 to 42	E	F	G	H	I	J	J				
	42 to 60	E	F	F	G	H	I	J				
	60 up	E	E	F	G	H	I	J				
14 (13 to 15½)	14 to 20	F	G	H	H	I	J	J				
	20 to 30	E	F	G	H	I	J	J				
	30 to 42	E	F	F	G	H	I	J	J			
	42 to 60	E	E	F	F	H	I	J	J	J		
	60 to 90	D	E	E	F	G	H	J	J	J		
	90 up	D	E	E	F	F	G	I	J	J		
17 (16 to 18½)	14 to 20	E	F	G	H	I	J	J				
	20 to 30	E	F	F	G	H	I	J				
	30 to 42	D	E	F	G	H	H	J	J	J		
	42 to 60	D	E	E	F	G	G	I	J	J	J	
	60 to 110	D	E	E	F	G	G	I	J	J	J	
	110 up	C	D	E	E	F	G	H	I	J	J	
20 (19 to 21½)	20 to 30	D	E	F	G	H	I	J	J			
	30 to 42	D	E	E	F	G	H	I	J	J		
	42 to 60	D	D	E	E	F	G	I	J	J	J	
	60 to 90	C	D	E	E	F	G	H	J	J	J	
	90 to 140	C	D	D	E	F	F	H	I	I	J	J
	140 up	C	D	D	E	F	F	H	H	I	J	J
24 (22 to 26)	20 to 30	D	E	E	F	G	H	I	J	J		
	30 to 42	C	D	E	F	G	G	I	J	J		
	42 to 60	C	D	D	E	F	G	H	I	J	J	
	60 to 90	C	D	D	E	F	F	H	I	J	J	J
	90 to 140	C	C	D	E	E	F	G	H	I	J	J
	140 up	C	C	D	E	E	F	G	H	I	I	J
30 (27 to 33)	30 to 42	C	D	D	E	F	G	H	I	J	J	
	42 to 60	C	C	D	D	F	F	H	H	I	J	
	60 to 90	B	C	C	D	E	F	G	H	I	J	J
	90 to 140	B	C	C	D	E	E	F	G	H	I	J
	140 to 180	B	C	C	D	E	E	F	G	H	I	J
	180 up	B	C	C	D	E	E	F	G	H	I	J

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* **Ward Harrison and C. E. Weitz, Illumination Design Data, LD-6A, Nela Park Eng. Dept., General Electric Company, 1936.**

TABLE 9-6.—ROOM INDEX.—(*Continued*)

		Ceiling height, feet										
For semi-indirect and indirect lighting		9 and 9½	10 to 11½	12 to 13½	14 to 16½	17 to 20	21 to 24	25 to 30	31 to 36	37 to 50		
		Mounting height above floor, feet										
For direct and semi-direct lighting		7 and 7½	8 and 8½	9 and 9½	10 to 11½	12 to 13½	14 to 16½	17 to 20	21 to 24	25 to 30	31 to 36	37 to 50
Room width, feet	Room length, feet	Room index										
36 (34 to 39)	30 to 42	B	C	D	E	F	F	H	I	I	J	
	42 to 60	B	C	C	D	E	F	G	H	I	J	J
	60 to 90	A	C	C	C	E	E	F	H	H	J	J
	90 to 140	A	B	C	C	D	E	F	G	H	I	J
	140 to 200	A	B	C	C	D	E	F	F	G	H	I
	200 up	A	B	C	C	D	E	F	F	G	H	I
(40 to 45)	42 to 60	A	B	C	C	E	F	G	H	I	I	J
	60 to 90	A	B	B	C	D	E	F	G	H	I	J
	90 to 140	A	B	B	C	D	D	E	F	G	H	J
	140 to 200	A	A	B	C	D	D	E	F	G	H	I
	200 up	A	A	B	C	D	D	E	F	F	G	I
(46 to 55)	42 to 60	A	A	B	C	D	E	F	G	H	I	J
	60 to 90	A	A	B	C	C	D	F	F	G	H	J
	90 to 140	A	A	A	C	C	D	E	F	F	G	I
	140 to 200	A	A	A	C	C	D	E	E	F	G	I
	200 up	A	A	A	C	C	D	E	E	F	G	H
60 (56 to 67)	60 to 90	A	A	A	B	C	D	E	F	G	H	I
	90 to 140	A	A	A	B	C	C	D	E	F	G	H
	140 to 200	A	A	A	B	C	C	D	E	E	F	H
	200 up	A	A	A	B	C	C	D	E	E	F	H
75 (68 to 90)	60 to 90	A	A	A	A	B	C	D	E	F	G	I
	90 to 140	A	A	A	A	B	C	D	E	F	F	H
	140 to 200	A	A	A	A	B	B	C	D	E	F	G
	200 up	A	A	A	A	B	B	C	D	E	F	G
over 90	60 to 90	A	A	A	A	B	C	D	E	F	G	H
	90 to 140	A	A	A	A	A	B	C	D	E	F	G
	140 to 200	A	A	A	A	A	B	C	D	E	F	G
	200 up	A	A	A	A	A	B	C	C	D	E	F

The spacing of lighting units is not influenced by the size or type of lamp used, but is regulated by the distribution characteristics of the reflector. Table 9-9 gives the allowable spacing applicable to all common types of reflecting and diffusing equipment employed for general illumination purposes. Where less than the maximum permissible spacing is employed the units may be mounted lower, if desired, but in no case should the mounting height be less than given in Table 9-10 for the actual spacing used.

The spacing-mounting height relations. apply not only to individual luminaires but equally so to the spacing between continuous or extended luminous beam panels, troughs, or sections of coves. There are, however, some exceptions in the case of equipments giving especially concentrated or exceptionally widespread distribution of light:

Concentrating louvered downlights or lens plates provide varying degrees of concentration. The spacing between units to provide uniformity over a general area, or lengthwise of a counter or work table should be regulated by the actual distribution characteristics of the unit. In general, the usual purpose is fulfilled by a spacing about one-third to one-half the values given in Table 9-9.

Semi-indirect and indirect systems diffuse the light widely from the ceiling as a secondary source of large area and the spacing between units may be about 2 ft. greater than indicated in Table 9-9.

Alternate mercury and incandescent units in combination systems should provide a fair degree of uniformity with either system used alone and should permit overlapping and blending of the light when used in combination. An alternate staggered layout with the spacing between units not to exceed 0.8 of the mounting height above the floor is recommended.

Supplementary Lighting.[1]—Severe visual tasks and modern merchandising methods require higher levels of illumination to eliminate eyestrain or to high light special displays, than are practical or economical to obtain from a system of general lighting alone. Supplementary lighting, as the name implies, should be employed in conjunction with a general lighting system, providing 10 to 20 foot-candles. High levels of illumination for better seeing defeat their own purpose if glare, harsh shadows, and severe contrasts between the brightly lighted are and surroundings are not eliminated.

The proper solution of supplementary lighting is not so much a question of computing the actual foot-candles delivered as it is method employed, the equipment used, and its location with respect to the specific seeing task or the particular type of display. When these factors are determined the lamp requirements may be computed from the distribution curve of the specific equipment or, as is often the case, may be determined experi-

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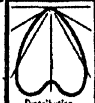
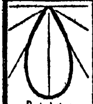
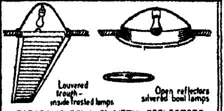
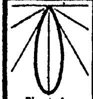
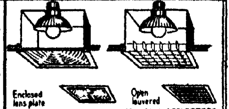
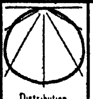
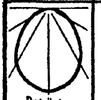
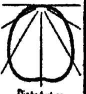
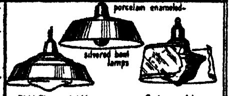
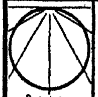
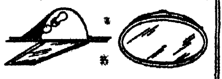
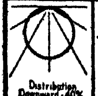
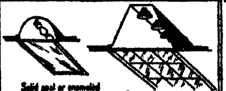
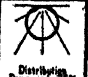
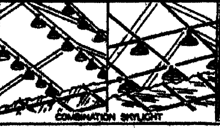
[1] HARRISON and WEITZ, *op. cit.*

TABLE 9-7.—FACTORS INFLUENCING

		TYPE OF DISTRIBUTION AND EFFICIENCY CLASSIFICATION	TYPICAL EQUIPMENT REPRESENTATIVE OF EACH GROUP	Ceiling	[illegible]			[illegible]			30%	
				Walls	[illegible]	30%	10%	[illegible]	30%	10%	30%	10%
				Room Index	COEFFICIENTS OF UTILIZATION[1]							
DIRECT CONCENTRATING TYPES	1	 Distribution Downward - 70%	Prismatic glass Mirrored glass Polished metal HIGH BAY OPEN REFLECTORS	J	.40	.38	.36	.39	.38	.36	.39	.36
				I	.48	.46	.46	.47	.46	.45	.46	.43
				H	.51	.51	.50	.50	.50	.49	.50	.48
				G	.55	.54	.54	.54	.52	.52	.52	.51
				F	.58	.56	.55	.55	.55	.54	.55	.53
				E	.60	.59	.58	.59	.58	.57	.57	.56
				D	.64	.61	.60	.62	.60	.60	.60	.59
				C	.65	.63	.61	.63	.62	.60	.60	.60
				B	.65	.64	.63	.64	.62	.62	.62	.61
				A	.66	.65	.64	.64	.63	.62	.62	.62
	2	 Distribution Downward - 50%	 Louvered trough - inside frosted lamps Open reflectors silvered bowl lamps PARABOLIC POLISHED METAL REFLECTORS	J	.29	.27	.26	.28	.27	.26	.28	.26
				I	.34	.33	.32	.34	.32	.32	.32	.31
				H	.37	.36	.36	.36	.36	.35	.36	.34
				G	.39	.39	.38	.38	.38	.37	.38	.36
				F	.41	.40	.39	.40	.39	.38	.39	.38
				E	.43	.42	.42	.42	.42	.40	.41	.40
				D	.46	.44	.43	.44	.43	.42	.42	.42
				C	.46	.45	.44	.45	.44	.43	.43	.42
				B	.47	.46	.45	.46	.44	.44	.44	.44
				A	.47	.46	46	.46	.45	.44	.44	.44
	3	 Distribution Downward - 30%	 Enclosed lens plate Open louvered PRISMATIC GLASS OR POLISHED METAL REFLECTORS	J	.17	.16	.16	.17	.16	.16	.17	.15
				I	.21	.20	.20	.20	.20	.19	.20	.19
				H	.22	.22	.21	.22	.21	.21	.21	.21
				G	.24	.23	.23	.23	.22	.22	.22	.22
				F	.25	.24	.24	.24	.23	.23	.23	.23
				E	.26	.25	.25	.25	.25	.24	.25	.24
				D	.27	.26	.26	.26	.26	.26	26	.25
				C	.28	.27	.26	.27	.26	.26	.26	.26
				B	.28	.27	.27	.27	.27	.26	.26	.26
				A	.28	.28	.27	.28	27	.27	.27	.26
DISTRIBUTING TYPES	4	 Distribution Downward - 75%	RLM Dome porcelain enameled-inside frosted lamp Mirrored or prismatic glass-inside frosted lamp DISTRIBUTING TYPE OPEN REFLECTORS	J	.34	.29	.24	.34	.29	.24	.28	.24
				I	.42	.38	.34	.42	.37	.33	.37	.33
				H	.46	.43	.39	.45	.42	.39	.42	.39
				G	.50	.47	.43	.49	.46	.43	.45	.42
				F	.53	.50	.46	.52	.49	.46	.48	.45
				E	.58	.55	.51	.57	.54	.51	.53	.51
				D	.62	.59	.56	.61	.58	.56	.58	.56
				C	.64	.61	.58	.63	.60	.58	.60	.58
				B	.67	.65	.63	.66	.64	.62	.63	.61
				A	.69	.67	.65	.67	.66	.64	.65	.63
	5	 Distribution Downward - 65%	RLM Dome porcelain enameled-white bowl lamp RLM Deep bowl porcelain enameled-inside frosted lamp DISTRIBUTING TYPE OPEN REFLECTORS	J	.32	.28	.25	.32	.28	.25	.27	.25
				I	.40	.36	.34	.39	.35	.33	.36	.33
				H	.43	.39	.37	.42	.39	.37	.39	.37
				G	.46	.43	.41	.45	.43	.41	.43	.41
				F	.48	.45	.43	.47	.45	.43	.45	.43
				E	.52	.50	.48	.51	.49	.47	.49	.47
				D	.56	.54	.52	55	.53	.51	.53	.51
				C	.57	.55	.53	.56	.54	.52	.54	.52
				B	.60	.58	.56	.59	.57	.55	.57	.55
				A	.61	.59	.57	.60	.58	.57	.58	.56
	6	 Distribution Downward - 60%	 porcelain enameled- silvered bowl lamps RLM Glassteel diffuser clear lamp Enclosing globe parchment shade LARGE AREA DIFFUSING REFLECTORS	J	.29	.24	.21	.28	.24	.21	.23	.21
				I	.36	.32	.29	.35	.31	.28	.30	.28
				H	.39	.36	.33	.38	.35	.33	.34	.32
				G	.43	.39	.36	.41	.38	.36	.37	.35
				F	.45	.42	.39	.43	.40	.38	.39	.38
				E	.49	.46	.44	.47	.45	.43	.43	.42
				D	.53	.50	.47	.51	.48	.46	.47	.46
				C	.54	.52	.49	.52	.50	.48	.48	.47
				B	.57	.55	.53	.55	.52	.51	.51	.50
				A	.59	.56	.54	.56	.54	.52	.52	.51
	7	 Distribution Downward - 55%	 * † Extended trough reflector cased opal glass cover Enameled metal reflector with diffusing cover plate LARGE AREA DIFFUSING PANELS	J	.26	.22	.19	.25	.22	.19	.21	.19
				I	.32	.29	.26	.31	.28	.26	.28	.26
				H	.35	.32	.30	.34	.32	.30	.31	.30
				G	.38	.35	.33	.37	.35	.32	.34	.32
				F	.40	.37	.35	.38	.36	.35	.36	.35
				E	.43	.41	.39	.42	.40	.38	.40	.38
				D	.46	.44	.42	.45	.43	.42	.43	.42
				C	.48	.46	.43	.46	.45	.43	.44	.43
				B	.50	.48	.46	.48	.47	.46	.46	.45
				A	.51	.49	.48	.50	.48	.47	.47	.46
	8	 Distribution Downward - 40%	 Solid opal or enameled glass cover Enclosed skylight LARGE AREA DIFFUSING PANELS	J	.19	.16	.14	.18	.16	.14	.16	.14
				I	.23	.21	.19	.23	.20	.19	.20	.19
				H	.25	.23	.22	.25	.23	.22	.23	.22
				G	.27	.25	.24	.27	.25	.24	.24	.24
				F	.29	.27	.25	.28	.26	.25	.26	.25
				E	.31	.30	.28	.31	.29	.28	.29	.28
				D	.34	.32	.30	.33	.32	.30	.31	.30
				C	.35	.33	.32	.34	.32	.32	.32	.31
				B	.36	.35	.34	.35	.34	.33	.34	.33
				A	.37	.36	.35	.36	.35	.34	.34	.34
	9	 Distribution Downward - 25%	 COMBINATION SKYLIGHT	J	.12	.10	.09	.12	.10	.09	.10	.09
				I	.14	.13	.12	.14	.13	.12	.13	.12
				H	.16	.15	.14	.16	.14	.14	.14	.14
				G	.17	.16	.15	.17	.16	.15	.15	.15
				F	.18	.17	.16	.18	.16	.16	.16	.16
				E	.20	.19	.18	.19	.18	.18	.18	.18
				D	.21	.20	.19	.20	.20	.19	.20	.19
				C	.22	.21	.20	.21	.20	.20	.20	.20
				B	.23	.22	.21	.22	.21	.21	.21	.20
				A	.23	.22	.22	.22	.22	.21	.22	.21

[1] The coefficients of utilization are calculated for the specific light output and distribution character-
sent the specific performance of any manufacturer's product. The light-output range given indicates
classifications, for which coefficients will be in proportion to the actual light output.

* WARD HARRISON and C. E. WEITZ, Illumination Design Data, Nela Park, Eng. Dept., General

† Reflector and Lamp Manufacturers Assoc.

SELECTION OF LIGHTING EQUIPMENT*

Maintenance factor, average conditions	
0.70	Light-output range, 68 to 75%; source brightness, low at normal angles of view because of large shielding angle; Foot-candles on the vertical, fair; reflected glare, likely to be severe because of reflected source brightness. Enameled reflectors of this shape do not produce a concentrated distribution and should not be confused with high bay reflectors.
0.70	Light-output range, 45 to 60%, depending on louver design and reflector size; coefficients calculated for 50% output. Louvered troughs likely to average 10% less; open, silvered-bowl lamp units may range from 10 to 20% higher than values shown. Specular surface parabolic reflectors essential. Source brightness, very low at normal angles of view. Foot-candles on the vertical, relatively low; reflected glare, likely to be severe with the louvered equipment. An effective means of securing high-level illumination with low brightness contrasts.
0.70	Light-output range, 27 to 35%, depending on adjustment or type of louver used; specular surface parabolic reflectors essential. Source brightness, low. Foot-candles on the vertical, extremely low. Care must be taken in location of units to avoid reflected glare from polished surfaces. Adaptable to many applications in combination with a fair proportion of indirect lighting. Lens plate units designed for wider distribution will have a higher output and fall in group 2.
0.75	Light-output range, 75% for R.L.M.† dome; 70 to 80% from extensive distribution prismatic or mirrored reflectors. Source brightness, uncomfortably high unless mounted either above 20 ft. or below eye level so that reflector shields the bright filament. Foot-candles on the vertical, fairly high. Reflected glare, extremely severe from polished surfaces. Highly efficient but limited in application to locations where conditions permit avoidance of direct and reflected glare.
0.75	Light-output range, 63 to 68%. Source brightness, moderately high but acceptably good for moderate levels of general illumination. Foot-candles on the vertical, fairly high. Reflected glare, considerably less than clear lamp units—the dome rating better than the deep bowl shape. The R.L.M. (white bowl lamp combination particularly) suitably meets a variety of industrial lighting requirements.
0.70	Light-output range, standard Glassteel 60% down, 7% up; silvered-bowl lamp and reflector 60 to 65% down, no upward light; shaded enclosing globe 50% down, 20% up; coefficients of utilization all about the same. Source brightness, relatively low. Foot-candles on the vertical, moderately high; reflected glare, suitably low for most industrial requirements. A group of equipment essential to high-quality industrial lighting.
0.70	Light-output range, 50 to 60% depending on reflector efficiency and transmission of glass cover plates; coefficients of utilization based on 55%; source brightness, generally low and controllable by increasing area; brightness limits for comfort range from 400 to 1,000 foot-lamberts; supplementary indirect lighting often used to relieve brightness contrasts against an otherwise dark ceiling.
0.65	This group is classified separately only because of lower light output. Light-output range, 35 to 45%, depending on construction and transmitting material; with extra heavy solid opal glass or low-transmission plastics, the efficiency range may extend to even lower limits; coefficients of utilization based on 40%; source brightness, controllable by source area and diffusion. The size and disposition of luminous panels and artificial skylight sections are matters largely regulated by architectural composition.
0.60	Light-output range, varies over a considerable range, depending on construction features and type of glass used. Coefficients of utilization based on 25%. Skylights serving both natural and artificial lighting penalize efficiency because there is no help from multiple reflections. Skylight framing and mullions and mechanical control devices likewise lessen efficiency. Quality factors with respect to direct and reflected glare and shadows are highly favorable.

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istics shown at the left. Equipments illustrated are typical and are not intended to repre-
variations to be expected between commercial equipments falling in any one of the several

Electric Company, 1936.

TABLE 9-8.—FOOT-CANDLE VALUES FOR DIFFERENT-SIZED LAMPS AND AREAS*

Area, square feet per lamp	Size of lamp		Coefficient of utilization																		
	Watts	Lumens	0.14	0.16	0.18	0.20	0.22	0.24	0.26	0.28	0.30	0.32	0.34	0.36	0.40	0.45	0.50	0.55	0.60	0.65	0.70
			Foot-candles																		
60	100	1,500	2.5	2.8	3.1	3.5	3.8	4.2	4.5	4.9	5.3	5 6	5.9	6 3	7.0	7.9	8.8	9.6	10.5	11.4	12.3
	150	2,500	4.1	4.7	5.3	5.8	6.3	7.0	7.6	8.2	8.8	9.3	10.0	10.5	11.7	13.1	14.6	16.0	17.5	19.0	20.4
	200	3,400	5.5	6.3	7.1	7.9	8 7	9.5	10.3	11.1	11 9	12 7	13.5	14.3	15.9	17.8	19.8	21.8	23.8	25.8	27.8
	300	5,500	9.0	10.3	11.6	12.8	14.1	15.4	16.7	18.0	19.3	20.5	21.8	23.1	25.7	28.9	32.1	35.3	38.5	41.7	45.0
	500	9,800	16.0	18.3	20.3	22.9	25.2	27.5	29.7	32.0	34.3	36 6	38.9	41.2	45.8	51.5	57.2	62.9	68.6	74.4	80.0
70	100	1,500	2.1	2.4	2.7	3.0	3.3	3.6	3.9	4.2	4.5	4 8	5.1	5.4	6.0	6.8	7.5	8.3	9.0	9 8	10.5
	150	2,500	3.5	4.0	4.5	5.0	5.4	6.0	6.5	7.0	7.5	8.0	8.5	9.0	10.0	11.3	12.5	13.8	15.0	16.3	17.5
	200	3,400	4.7	5.5	6.1	6.8	7.5	8.2	8 9	9.5	10.2	10.9	11.5	12.2	13.6	15.3	17.0	18 7	20.4	22.1	23.8
	300	5,500	7.7	8.8	9.9	11.0	12.1	13.2	14 3	15.4	16.5	17.6	18.7	19.8	22.0	24.8	27.5	30.2	33.0	35.8	38.5
	500	9,800	13.7	15.7	17.6	19.6	21.6	23.5	25.5	27.4	29.4	31.4	33.3	35.3	39.2	44.1	49.0	54.0	58.8	63.7	68.5
80	100	1,500	1.8	2.1	2.4	2.6	2.9	3.1	3.4	3.7	3.9	4.1	4.4	4 6	5.2	5.9	6.6	7.2	7.9	8.5	9.2
	150	2,500	3.1	3.5	3.9	4.4	4.8	5.3	5.7	6 1	6.6	7.0	7.4	7.9	8.8	9.8	10.9	12.0	13.1	14.2	15.3
	200	3,400	4.2	4.8	5.4	5.9	6.5	7.1	7.7	8 3	8.9	9.5	10.1	10.7	11.9	13.4	14.9	16.4	17.9	19.3	20.8
	300	5,500	6.7	7.7	8.7	9.6	10.6	11.5	12.5	13.5	14.5	15.4	16.4	17.3	19.3	21.6	24.1	26.5	28.9	31.3	33.7
	500	9.800	12.0	13.7	15.5	17.2	18.9	20.5	22.3	24.0	25.7	27 5	29.1	30.9	34.4	38.6	43.0	47.2	51.5	55.8	60.0
90	100	1.500	1.6	1.9	2.1	2.3	2.6	2.8	3.0	3.3	3.5	3.7	4.0	4.2	4.7	5.2	5 8	6.4	7.0	7.6	8.2
	150	2,500	2.7	3.1	3.4	3.9	4.2	4.7	5.1	5.5	5.8	6.2	6.6	7.0	7.8	8.8	9.7	10.7	11.7	12.6	13.6
	200	3,400	3.7	4.2	4.8	5.3	5.8	6.4	6.9	7.4	7.9	8.5	9.0	9.5	10.6	11.9	13.2	14.5	15.9	17.2	18.5
	300	5,500	6.0	6.9	7.7	8.6	9.4	10.3	11.1	12.0	12.8	13.7	14.5	15.4	17.1	19.3	21.4	23.5	25.7	27.8	30.0
	500	9,800	10.7	12.2	13.7	15.2	16.8	18.3	19.8	21.4	22.9	24.4	25.0	27.4	30.5	34.3	38.1	42.0	45.8	49.5	53.5
	750	14.550	15.8	18.1	20.4	22.6	24.9	27.2	29.4	31.7	34.0	36.2	38.5	40.7	45.3	51.0	56.6	62.3	67.9	73.6	79.2
100	100	1,500	1.5	1.7	1.9	2.1	2.3	2.5	2.7	2.9	3.1	3.4	3.6	3.8	4.2	4.6	5.3	5.8	6.3	6.8	7.4
	150	2,500	2.5	2.8	3.2	3.5	3.8	4.2	4.6	4.9	5.3	5 6	6.0	6.3	7.0	7.9	8.8	9.6	10.5	11.4	12.3
	200	3,400	3.3	3.8	4.3	4.8	5.2	5.7	6.2	6.7	7.1	7 6	8.1	8.6	9.5	10.7	11.9	13.1	14.3	15.5	16.7
	300	5,500	5.4	6.2	6.9	7.7	8.5	9.2	10.0	10.8	11.5	12.3	13.1	13.9	15.4	17.3	19.3	21.2	23.1	25.0	27.0
	500	9,800	9.6	11.0	12.3	13.7	15.1	16.5	17.7	19.2	20.6	21.9	23.3	24.7	27.4	30.9	34.3	37.7	41.2	44.6	48.0
	750	14,550	14.3	16.3	18.3	20.4	22.4	24.5	26.5	28.6	30.6	32.6	34.7	36.7	40.8	45.9	51.0	56.1	61.2	66.3	71.4
110	100	1,500	1.3	1.5	1.7	1.9	2.1	2.3	2.5	2.7	2.9	3.0	3.2	3.4	3.8	4.3	4.8	5.2	5.7	6.2	6.7
	150	2,500	2.2	2.5	2.9	3.2	3.5	3.8	4.1	4.5	4.8	5.1	5.4	5.7	6.4	7.2	8.0	8.8	9.5	10.3	11.1
	200	3.400	3.0	3.5	3.9	4.3	4.8	5.2	5.6	6.1	6.5	6.9	7.4	7.8	8.7	9.7	10.8	11.9	13.0	14.1	15.2

110	300	5,500	4.9	5.6	6.2	7.0	7.7	8.4	9.1	9.8	10.5	11.2	11.9	12.6	14.0	15.7	17.5	19.2	21.0	22.7	24.5
	500	9,800	8.7	10.0	11.2	12.5	13.7	14.9	16.2	17.5	18.7	20.0	21.2	22.5	25.0	28.1	31.2	34.3	37.5	40.6	43.7
	750	14,550	13.0	14.8	16.7	18.5	20.4	22.2	24.0	26.0	27.8	29.6	31.5	33.4	37.1	41.7	46.3	51.0	55.6	60.2	64.8
120	100	1,500	1.2	1.4	1.6	1.8	1.9	2.1	2.3	2.5	2.6	2.8	3.0	3.1	3.5	3.9	4.4	4.8	5.2	5.7	6.1
	150	2,500	2.0	2.3	2.6	2.9	3.2	3.5	3.8	4.1	4.4	4.7	5.0	5.3	5.8	6.6	7.3	8.0	8.8	9.5	10.2
	200	3,400	2.8	3.2	3.6	4.0	4.4	4.8	5.2	5.6	5.9	6.4	6.7	7.2	8.0	9.0	10.0	11.0	12.0	13.0	14.0
	300	5,500	4.5	5.1	5.8	6.4	7.1	7.7	8.4	9.0	9.6	10.3	10.9	11.5	12.8	14.4	16.0	17.6	19.2	20.8	22.4
	500	9,800	8.0	9.1	10.3	11.4	12.6	13.7	14.9	16.0	17.2	18.3	19.4	20.6	22.9	25.7	28.6	31.4	34.3	37.2	40.0
	750	14,550	11.9	13.6	15.3	17.0	18.7	20.4	22.1	23.8	25.5	27.2	28.9	30.6	34.0	38.2	42.5	46.7	51.0	55.2	59.4
130	150	2,500	1.9	2.2	2.4	2.7	2.9	3.2	3.5	3.8	4.0	4.3	4.6	4.8	5.4	6.1	6.7	7.4	8.1	8.8	9.4
	200	3,400	2.6	2.9	3.3	3.7	4.0	4.4	4.8	5.1	5.5	5.9	6.2	6.6	7.3	8.2	9.2	10.1	11.0	11.9	12.8
	300	5,500	4.1	4.7	5.3	5.9	6.5	7.1	7.7	8.3	8.9	9.5	10.1	10.6	11.8	13.3	14.8	16.3	17.8	19.2	20.7
	500	9,800	7.4	8.4	9.5	10.6	11.6	12.7	13.7	14.8	15.8	16.9	18.0	19.0	21.1	23.8	26.4	29.0	31.7	34.3	37.0
	750	14,550	11.0	12.5	14.1	15.6	17.2	18.9	20.4	22.0	23.6	25.0	26.7	28.2	31.3	35.2	39.1	43.0	47.0	50.8	54.7
140	150	2,500	1.8	2.0	2.3	2.5	2.7	3.0	3.3	3.5	3.8	4.0	4.3	4.5	5.0	5.6	6.3	6.9	7.5	8.1	8.8
	200	3,400	2.4	2.7	3.1	3.4	3.7	4.1	4.4	4.8	5.1	5.4	5.8	6.1	6.8	7.6	8.5	9.3	10.2	11.0	11.9
	300	5,500	3.8	4.4	5.0	5.5	6.0	6.6	7.1	7.7	8.2	8.8	9.3	9.9	11.0	12.4	13.7	15.1	16.5	17.9	19.3
	500	9,800	6.9	7.8	8.8	9.8	10.8	11.8	12.8	13.7	14.7	15.7	16.7	17.6	19.6	22.1	24.5	27.0	29.4	31.8	34.3
	750	14,550	10.2	11.7	13.1	14.6	16.0	17.5	18.9	20.4	21.8	23.3	24.8	26.2	29.1	32.8	36.4	40.0	43.7	47.3	51.0
150	150	2,500	1.6	1.9	2.1	2.3	2.5	2.8	3.0	3.3	3.5	3.7	4.0	4.2	4.7	5.3	5.8	6.4	7.0	7.6	8.2
	200	3,400	2.2	2.5	2.9	3.2	3.5	3.8	4.1	4.4	4.8	5.1	5.4	5.7	6.3	7.1	7.9	8.8	9.5	10.3	11.1
	300	5,500	3.6	4.1	4.6	5.1	5.6	6.2	6.7	7.2	7.7	8.2	8.7	9.2	10.3	11.5	12.8	14.2	15.4	16.7	18.0
	500	9,800	6.4	7.3	8.2	9.1	10.1	11.0	11.9	12.8	13.7	14.6	15.5	16.4	18.3	20.6	22.8	25.2	27.4	29.7	32.0
	750	14,550	9.5	10.8	12.2	13.6	14.9	16.3	17.7	19.0	20.4	21.7	23.1	24.4	27.2	30.6	34.0	37.3	40.7	44.1	47.5
160	150	2,500	1.5	1.8	2.0	2.2	2.4	2.6	2.8	3.1	3.3	3.5	3.7	3.9	4.4	4.9	5.5	6.0	6.6	7.1	7.7
	200	3,400	2.1	2.4	2.7	3.0	3.3	3.6	3.9	4.2	4.5	4.8	5.1	5.4	5.9	6.7	7.4	8.2	8.9	9.7	10.4
	300	5,500	3.4	3.9	4.3	4.8	5.3	5.8	6.3	6.7	7.2	7.7	8.2	8.7	9.6	10.8	12.0	13.2	14.4	15.6	16.8
	500	9,800	6.0	6.9	7.7	8.6	9.4	10.3	11.2	12.0	12.9	13.7	14.6	15.4	17.2	19.3	21.4	23.6	25.7	27.9	30.0
	750	14,550	8.9	10.2	11.4	12.7	14.0	15.3	16.6	17.8	19.1	20.4	21.7	22.9	25.4	28.6	31.8	35.0	38.2	41.4	44.5
	1,000	20,700	12.7	14.5	16.3	18.1	19.9	21.7	23.5	25.4	27.2	29.0	30.8	32.6	36.2	40.8	45.3	49.8	54.3	58.9	63.4
170	150	2,500	1.4	1.6	1.9	2.1	2.2	2.5	2.7	2.9	3.1	3.3	3.5	3.7	4.1	4.6	5.1	5.7	6.2	6.7	7.2
	200	3,400	2.0	2.2	2.5	2.8	3.1	3.4	3.6	3.9	4.2	4.5	4.8	5.0	5.6	6.3	7.0	7.7	8.4	9.1	9.8
	300	5,500	3.2	3.6	4.1	4.5	5.0	5.4	5.9	6.4	6.8	7.2	7.7	8.2	9.1	10.2	11.3	12.5	13.6	14.7	15.9
	500	9,800	5.7	6.5	7.3	8.1	8.9	9.7	10.5	11.3	12.1	12.9	13.7	14.5	16.2	18.2	20.2	22.2	24.2	26.2	28.3
	750	14,550	8.4	9.6	10.8	12.0	13.2	14.4	15.6	16.8	18.0	19.2	20.3	21.6	24.0	27.0	30.0	33.0	36.0	39.0	42.0
	1,000	20,700	11.9	13.6	15.3	17.0	18.7	20.4	22.2	23.9	25.6	27.3	29.0	30.7	34.1	38.3	42.6	46.9	51.1	55.4	59.6

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* WARD HARRISON and C. E. WEITZ, Illumination Design Data, LD-6A, Nela Park Eng. Dept., General Electric Company, 1936.

TABLE 9-8.—FOOT-CANDLE VALUES FOR DIFFERENT-SIZED LAMPS AND AREAS.*—(*Continued*)

Area, square feet per lamp	Size of lamp		Coefficient of utilization																		
	Watts	Lumens	0.14	0.16	0.18	0.20	0.22	0.24	0.26	0.28	0.30	0.32	0.34	0.36	0.40	0.45	0.50	0.55	0.60	0.65	0.70
			Foot-candles																		
180	150	2,500	1.4	1.5	1.8	1.9	2.1	2.3	2.5	2.7	2.9	3.1	3.3	3.5	3.9	4.4	4.9	5.3	5.8	6.3	6.8
	200	3,400	1.9	2.1	2.4	2.6	2.9	3.2	3.4	3.7	4.0	4.2	4.5	4.8	5.3	6.0	6.6	7.3	7.9	8.6	9.3
	300	5,500	3.0	3.4	3.9	4.3	4.7	5.1	5.6	6.0	6.4	6.8	7.3	7.7	8.6	9.6	10.7	11.8	12.8	13.9	15.0
	500	9,800	5.3	6.1	6.9	7.6	8.4	9.1	9.9	10.7	11.4	12.2	12.9	13.8	15.3	17.2	19.1	21.0	22.8	24.8	26.7
	750	14,550	7.9	9.1	10.2	11.3	12.4	13.6	14.7	15.8	17.0	18.1	19.2	20.4	22.6	25.4	28.3	31.1	34.0	36.8	39.6
	1,000	20,700	11.3	12.9	14.5	16.1	17.7	19.3	20.9	22.6	24.2	25.8	27.4	29.0	32.2	36.2	40.2	44.2	48.3	52.3	56.3
200	200	3,400	1.7	1.9	2.1	2.4	2.6	2.9	3.1	3.3	3.6	3.8	4.0	4.3	4.8	5.4	6.0	6.6	7.2	7.7	8.3
	300	5,500	2.7	3.1	3.5	3.8	4.2	4.6	5.0	5.4	5.8	6.2	6.5	6.9	7.7	8.7	9.6	10.6	11.6	12.5	13.5
	500	9,800	4.8	5.5	6.2	6.9	7.6	8.2	8.9	9.6	10.3	11.0	11.7	12.4	13.7	15.5	17.2	18.9	20.6	22.3	24.0
	750	14,550	7.1	8.1	9.2	10.2	11.2	12.2	13.2	14.3	15.3	16.3	17.3	18.3	20.4	22.9	25.4	28.0	30.6	33.1	35.6
	1,000	20,700	10.2	11.6	13.1	14.5	16.0	17.4	18.8	20.3	21.7	23.2	24.6	26.1	29.0	32.6	36.2	40.0	43.5	47.2	50.8
	1,500	33,000	16.2	18.5	20.8	23.2	25.4	27.7	30.0	32.4	34.6	37.0	39.2	41.6	46.3	52.0	57.8	63.6	69.4	75.2	81.0
220	200	3,400	1.5	1.7	2.0	2.2	2.4	2.6	2.8	3.0	3.3	3.5	3.7	3.9	4.3	4.9	5.4	6.0	6.5	7.0	7.6
	300	5,500	2.4	2.8	3.1	3.5	3.8	4.2	4.5	4.9	5.2	5.6	5.9	6.3	7.0	7.9	8.8	9.6	10.5	11.4	12.3
	500	9,800	4.4	5.0	5.6	6.2	6.9	7.5	8.1	8.7	9.3	10.0	10.6	11.2	12.5	14.0	15.6	17.2	18.7	20.3	21.8
	750	14,550	6.5	7.4	8.3	9.3	10.2	11.1	12.1	13.0	13.9	14.8	15.7	16.7	18.6	20.9	23.2	25.5	27.8	30.2	32.5
	1,000	20,700	9.2	10.5	11.9	13.2	14.5	15.8	17.1	18.5	19.7	21.1	22.4	23.7	26.4	29.6	33.0	36.2	39.5	42.8	46.1
	1,500	33,000	14.7	16.8	18.9	21.0	23.1	25.2	27.3	29.4	31.5	33.7	35.7	37.9	42.1	47.3	52.6	57.8	63.1	68.4	73.6
240	200	3,400	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0	3.2	3.4	3.6	4.0	4.5	5.0	5.5	5.9	6.4	6.9
	300	5,500	2.2	2.6	2.9	3.2	3.5	3.8	4.2	4.5	4.8	5.1	5.4	5.8	6.4	7.2	8.0	8.8	9.6	10.4	11.2
	500	9,800	4.0	4.6	5.2	5.7	6.3	6.9	7.4	8.0	8.6	9.2	9.7	10.3	11.4	12.9	14.3	15.8	17.2	18.6	20.0
	750	14,550	5.9	6.8	7.6	8.5	9.3	10.1	11.0	11.9	12.7	13.6	14.4	15.3	17.0	19.0	21.2	23.3	25.5	27.5	29.7
	1,000	20,700	8.5	9.7	10.9	12.1	13.3	14.5	15.7	16.9	18.1	19.4	20.6	21.7	24.2	27.2	30.2	33.2	36.3	39.2	42.3
	1,500	33,000	13.5	15.4	17.4	19.3	21.2	23.1	25.0	27.0	28.9	30.8	32.7	34.7	38.6	43.4	48.2	53.0	57.8	62.6	67.5
260	200	3,400	1.3	1.5	1.6	1.8	2.0	2.2	2.4	2.6	2.7	2.9	3.1	3.3	3.7	4.1	4.6	5.0	5.5	6.0	6.4
	300	5,500	2.1	2.4	2.7	3.0	3.3	3.6	3.9	4.2	4.4	4.7	5.0	5.3	5.9	6.7	7.4	8.2	8.9	9.6	10.4
	500	9,800	3.7	4.2	4.7	5.3	5.8	6.3	6.9	7.4	7.9	8.5	9.0	9.5	10.6	11.9	13.2	14.5	15.8	17.2	18.5
	750	14,550	5.5	6.3	7.1	7.8	8.6	9.4	10.2	10.9	11.8	12.5	13.3	14.1	15.7	17.6	19.6	21.5	23.5	25.4	27.4
	1,000	20,700	7.8	8.9	10.0	11.2	12.3	13.4	14.5	15.6	16.7	17.9	19.0	20.1	22.3	25.1	27.9	30.7	33.5	36.3	39.1
	1,500	33,000	12.5	14.2	16.0	17.8	19.6	21.3	23.1	24.9	26.7	28.5	30.2	32.0	35.6	40.0	44.5	49.0	53.4	57.9	62.3

280	200	3,400	1.2	1.4	1.6	1.7	1.9	2.1	2.3	2.4	2.6	2.8	3.0	3.1	3.5	3.9	4.4	4.8	5.1	5.7	6.0
	300	5,500	1.9	2.2	2.5	2.8	3.0	3.3	3.6	3.9	4.1	4.4	4.7	5.0	5.5	6.2	6.9	7.6	8.3	8.9	9.6
	500	9,800	3.4	3.9	4.4	4.9	5.4	5.9	6.4	6.9	7.3	7.9	8.3	8.8	9.8	11.0	12.3	13.5	14.7	15.9	17.2
	750	14,550	5.1	5.8	6.5	7.3	8.0	8.7	9.5	10.2	10.9	11.6	12.3	13.1	14.6	16.4	18.2	20.0	21.8	23.7	25.5
	1,000	20,700	7.2	8.3	9.3	10.3	11.4	12.4	13.5	14.5	15.5	16.5	17.6	18.6	20.7	23.3	25.9	28.4	31.0	33.6	36.2
	1,500	33,000	11.6	13.2	14.9	16.5	18.2	19.8	21.4	23.1	24.7	26.4	28.0	29.8	33.0	37.2	41.3	45.5	49.5	53.7	57.8
320	200	3,400	1.0	1.2	1.3	1.5	1.6	1.8	1.9	2.1	2.2	2.4	2.5	2.7	3.0	3.4	3.7	4.1	4.5	4.9	5.2
	300	5,500	1.7	1.9	2.2	2.4	2.6	2.9	3.1	3.4	3.6	3.9	4.1	4.3	4.8	5.4	6.0	6.6	7.2	7.8	8.4
	500	9,800	3.0	3.4	3.9	4.3	4.7	5.1	5.6	6.0	6.4	6.9	7.3	7.7	8.6	9.7	10.7	11.8	12.9	14.0	15.0
	750	14,550	4.5	5.1	5.7	6.4	7.0	7.6	8.3	8.9	9.5	10.2	10.8	11.5	12.7	14.3	15.9	17.5	19.1	20.6	22.3
	1,000	20,700	6.3	7.3	8.2	9.1	10.0	10.9	11.8	12.7	13.6	14.5	15.4	16.3	18.1	20.4	22.6	25.0	27.2	29.4	31.7
	1,500	33,000	10.1	11.6	13.0	14.5	15.9	17.3	18.7	20.2	21.7	23.2	24.5	26.0	28.9	32.5	36.1	39.8	43.4	47.0	50.6
360	300	5,500	1.5	1.7	1.9	2.1	2.4	2.6	2.8	3.0	3.2	3.4	3.6	3.8	4.3	4.8	5.3	5.9	6.4	7.0	7.5
	500	9,800	2.7	3.0	3.4	3.8	4.2	4.6	4.9	5.3	5.7	6.1	6.5	6.9	7.6	8.6	9.5	10.5	11.4	12.4	13.4
	750	14,550	4.0	4.5	5.1	5.7	6.2	6.8	7.4	7.9	8.5	9.1	9.6	10.2	11.3	12.8	14.2	15.6	17.0	18.4	19.8
	1,000	20,700	5.6	6.4	7.2	8.0	8.9	9.7	10.5	11.3	12.1	12.9	13.7	14.5	16.1	18.1	20.2	22.2	24.2	26.2	28.2
	1,500	33,000	9.0	10.3	11.6	12.8	14.1	15.4	16.7	18.0	19.3	20.6	21.8	23.1	25.7	28.9	32.1	35.3	38.6	41.8	45.0
400	300	5,500	1.4	1.5	1.7	1.9	2.1	2.3	2.5	2.7	2.9	3.1	3.3	3.5	3.9	4.3	4.8	5.3	5.8	6.3	6.7
	500	9,800	2.4	2.7	3.1	3.4	3.8	4.1	4.5	4.8	5.1	5.5	5.8	6.2	6.9	7.7	8.6	9.4	10.3	11.2	12.0
	750	14,550	3.6	4.1	4.6	5.1	5.6	6.1	6.6	7.1	7.6	8.2	8.7	9.2	10.2	11.5	12.7	14.0	15.3	16.5	17.8
	1,000	20,700	5.1	5.8	6.5	7.3	8.0	8.7	9.4	10.2	10.8	11.6	12.3	13.1	14.5	16.4	18.1	20.0	21.8	23.6	25.4
	1,500	33,000	8.1	9.3	10.4	11.6	12.7	13.9	15.0	16.2	17.3	18.5	19.7	20.8	23.2	26.0	28.9	31.8	34.7	37.6	40.5
450	300	5,500	1.2	1.4	1.6	1.7	1.9	2.1	2.3	2.4	2.6	2.8	3.0	3.1	3.5	3.9	4.4	4.8	5.1	5.6	6.0
	500	9,800	2.1	2.4	2.7	3.1	3.4	3.7	4.0	4.3	4.6	4.9	5.2	5.5	6.1	6.9	7.6	8.4	9.2	9.9	10.7
	750	14,550	3.2	3.6	4.1	4.5	5.0	5.4	5.9	6.3	6.8	7.2	7.7	8.1	9.1	10.2	11.3	12.4	13.6	14.7	15.8
	1,000	20,700	4.5	5.2	5.8	6.5	7.1	7.7	8.4	9.0	9.7	10.3	10.9	11.6	12.9	14.5	16.1	17.7	19.4	21.0	22.6
	1,500	33,000	7.2	8.2	9.3	10.3	11.3	12.4	13.4	14.4	15.4	16.4	17.5	18.5	20.6	23.2	25.7	28.3	30.8	33.4	36.0
500	300	5,500	1.1	1.2	1.4	1.5	1.7	1.8	2.0	2.2	2.3	2.5	2.6	2.8	3.1	3.5	3.8	4.2	4.6	5.0	5.4
	500	9,800	1.9	2.2	2.5	2.7	3.0	3.3	3.6	3.8	4.1	4.4	4.7	4.9	5.5	6.2	6.9	7.6	8.2	8.9	9.6
	750	14,550	2.8	3.3	3.7	4.1	4.5	4.9	5.3	5.7	6.1	6.5	6.9	7.3	8.1	9.2	10.2	11.2	12.2	13.3	14.3
	1,000	20,700	4.1	4.6	5.2	5.8	6.4	7.0	7.5	8.1	8.7	9.3	9.8	10.4	11.6	13.0	14.5	16.0	17.4	18.8	20.3
	1,500	33,000	6.5	7.4	8.3	9.2	10.2	11.1	12.0	12.9	13.9	14.8	15.7	16.6	18.5	20.8	23.1	25.5	27.7	30.0	32.4

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* WARD HARRISON and C E WEITZ, Illumination Design Data, LD-6A, Nela Park Eng Dept , General Electric Company, 1936

TABLE 9-9.—ALLOWABLE SPACING BETWEEN LIGHT SOURCES*

Ceiling height (or height in the clear), feet	Spacing between outlets, feet		Spacing between outside outlets and wall		Approximate area per outlet at usual spacings, square feet
	Usual	Maximum, for units at ceiling	Aisles or storage next to wall	Maximum for desks, work-benches, etc., against wall, feet	
8	7	7½	Usually	3	50 to 60
9	8	8		3	60 to 70
10	9	9	one-half	3½	70 to 85
11	10	10½		3½	85 to 100
12	10 to 12	12	actual	3½ to 4	100 to 150
13	10 to 12	13		3½ to 4½	100 to 150
14	10 to 13	15	spacing	4 to 5	100 to 170
15	10 to 13	17		4 to 5	100 to 170
16	10 to 13	19	between	4 to 6	100 to 170
18	10 to 20	21		4 to 6	100 to 400
20 or more	18 to 24	24	units	5 to 7	300 to 500

* WARD HARRISON and C E WEITZ, Illumination Design Data, LD-6A, Nela Park Eng. Dept., General Electric Company, 1936.

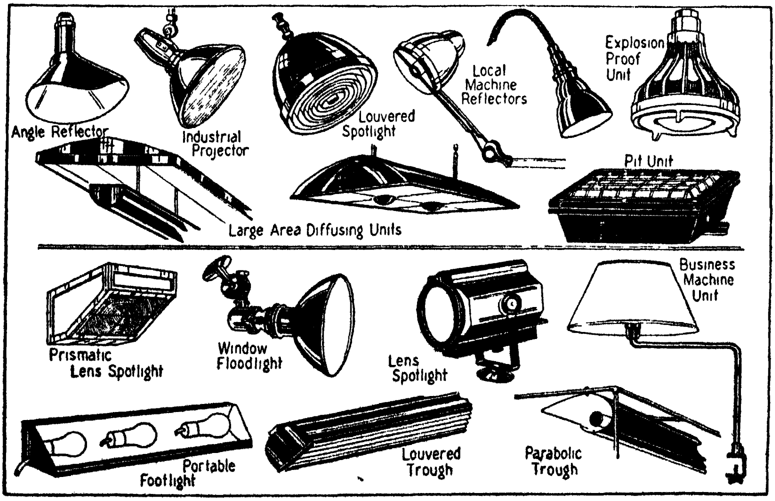

FIG. 9-8.—Typical supplementary or specialized lighting equipment.

mentally. Some of the equipment for supplementary lighting are described in the following paragraphs and are illustrated in Fig. 9-8.

The foot-candles recommended for supplementary lighting can be roughly grouped into three general classifications according to the difficulty of the visual tasks involved. These classifications, referred to in Table 9-4, are as follows:

Class A. 100 *Foot-candles or More.*—Necessary where visual tasks involve (1) extremely fine detail, (2) materials of exceptionally low or poor contrast, (3) prolonged duration.

Class B. 50 *to* 100 *Foot-candles.*—Necessary where visual tasks involve (1) fine detail, (2) medium contrast in materials, (3) less prolonged duration.

TABLE 9-10.—MOUNTING HEIGHT OF LIGHT SOURCES*

Direct and semidirect lighting units				Semi-indirect and indirect lighting	
Actual spacing between units, feet	Distance of units from floor not less than, feet	Desirable mounting height in industrial interiors	Desirable mounting height in commercial interiors	Actual spacing between units, feet	Recommended suspension length, top of bowl to ceiling, feet
7	8	12 ft. above floor if possible—to avoid glare, and still be within reach from stepladder for cleaning. Where units are to be mounted much more than 12 ft. it is usually desirable to mount the units at ceiling or on roof trusses.	The actual hanging height should be governed largely by general appearance but, particularly in offices and drafting rooms, the minimum values shown in the second column should not be violated.	7	1 to 3
8	8½			8	1 to 3
9	9			9	1 to 3
10	10			10	1½ to 3
11	10½			11	2 to 3
12	11			12	2 to 3
14	12½			14	2½ to 4
16	14			16	3 to 4
18	15			18	3 to 4
20	16			20	4 to 5
22	18			22	4 to 5
24	20			24	4 to 6

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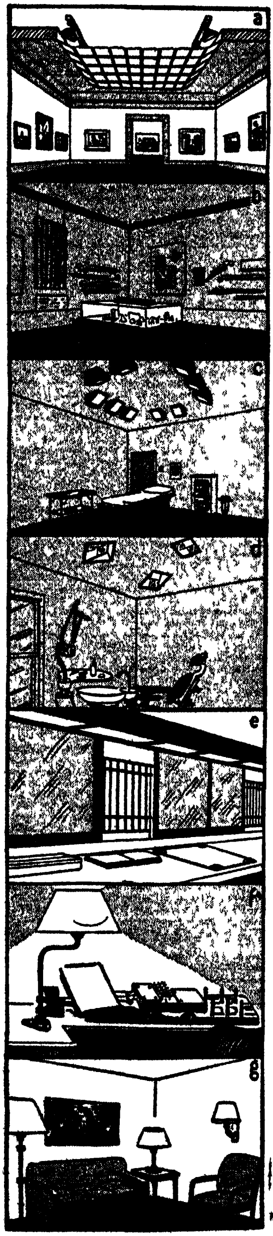
* **WARD HARRISON and C. E. WEITZ, Illumination Design Data, LD-6A, Nela Park Eng. Dept., General Electric Company, 1936.**



a Art Galleries—A special solution is usually necessary for each installation In general the hanging areas should be lighted in some such manner as illustrated, with concealed projectors behind stippled or ribbed glass sections Illumination of the order of 50 foot-candles will be provided by 300-watt daylight lamps spaced 1½ to 2 ft apart The supplementary lighting is usually coordinated with an artificial skylight which may furnish about 5 foot-candles of general illumination

b Museums Special Exhibits—Special study should be made of each exhibit and the lighting fitted to the specific conditions encountered Many cases are suitably lighted with showcase equipment while others may require special color and natural shadow effects Broad flat cases may be lighted by trough equipment, as illustrated

c Hospital Operating Tables—The best practice is to use a localized general system with concentrating reflectors or lens plates to concentrate the light on the operating zone from all directions in order to avoid harsh shadows Two hundred foot-candles or more should be provided Adjustable spotlights will also be found useful when used with general illumination of 20 foot-candles or more to relieve contrasts and shadows

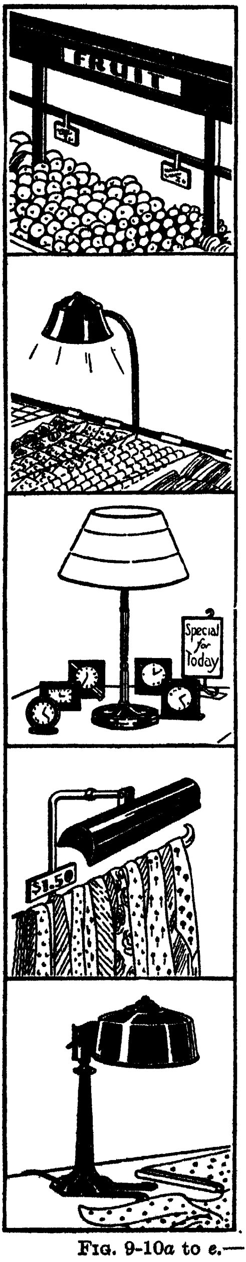
d Dental Chairs—General illumination of at least 20 foot-candles should be supplemented with two or three 150-watt lens units or louvered spotlights directed at the operating area

e Counters and Dealing Shelves—In bank cages and ticket offices supplementary trough lighting equipment is usually located at the top of the cages to produce a band of light lengthwise of the counter Troughs may be covered with diffusing glass or fitted with longitudinal louvers to shield the lamps Sixty-watt lamps on 15- to 18-in centers will generally be adequate

f Business-machine Lighting—Where power is brought to the desk for the operation of business machines and where the work is of a kind that is particularly difficult to see, bracket type units similar to the I E S reading lamp permanently positioned on key-punch machines, copyholders, and index references will when equipped with 100-watt lamps provide 60 foot-candles of supplementary lighting on the work For ordinary typing work, general lighting of 30 foot-candles is recommended

g Reading and Writing Rooms—In hotels, libraries, waiting rooms, and hospitals supplementary lighting should be provided by means of portable reading lamps, in addition to the general illumination Certified I E S lamps in floor, table, and wall-type models are recommended from the standpoint of diffusion and distribution of light On writing desks the best location for portables is at the left-hand side of the desk

Fig. 9-9*a* to *g*.—Special applications.



a. Continuous trough reflectors for counters, tables, island displays mounted 3 ft. above display with 40- to 60-watt lamps 10 to 15 in. apart should produce 50 to 100 foot-candles on the merchandise. Translucent panels in the sides provide effective changeable advertising.

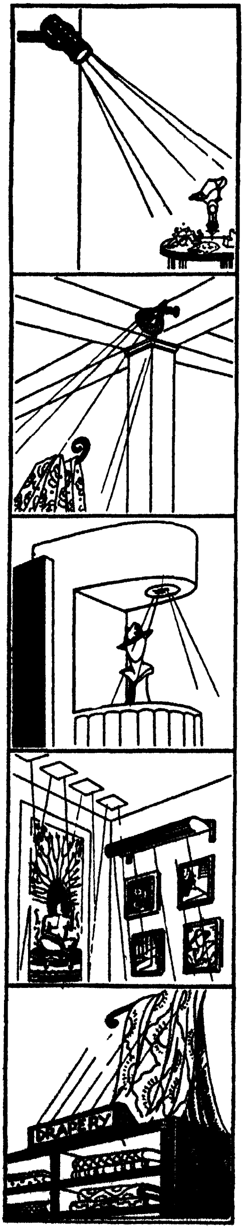
b. Individual counter brackets about 2 ft. above merchandise, spaced 3 ft. apart and lamped with 60- to 100-watt lamps will provide 75 to 100 foot-candles on the display. Daylight lamps are used effectively for colored ornaments, costume jewelry and notions.

c. For small individual table displays an I.E.S. table lamp with 100- or 150-watt lamp will provide 30 to 60 foot-candles directly on the display and will contribute also to the general lighting. It creates intimate, attractive display settings.

d. Small metal bracket-type reflectors with lumiline or regular 25- or 40-watt tubular bulb lamps effectively emphasize small vertical display racks, stands, and cabinets.

e. Counter units for accurate color matching of hose and shoes, thread and fabrics use blue glass absorbing filters to produce white light. A 300-watt unit with a 50 per cent absorption plate (5000°K. color temperature) should produce 200 foot-candles at 18 in. A second circuit with clear unmodified Mazda lamps to produce approximately the same illumination should be provided for comparison purposes.

FIG. 9-10*a* to *e*.—Merchandise display. Counter and table units.



f. Small compact lens posts available in both 250- and 400-watt size mounted on columns, or ceiling brackets, give sales emphasis to small counter or table displays. Adjustable in spot size for 12- to 48-in. diameter spot at 10 ft. The 250-watt unit at 10 ft. will deliver 200 to 250 foot-candles, with a 12- to 15-in. spot size; the 400-watt unit, 350 to 450 foot-candles.

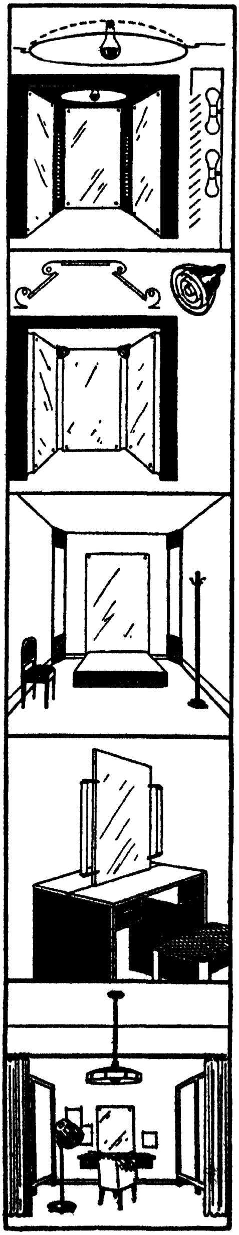
g. Louvered concentrating reflector spotlights available in 200- to 500-watt sizes give a less sharply defined beam than lens units. The spot size cannot be adjusted except by changing projection distances. A 200-watt unit at 10 ft. will produce about 90 foot-candles.

h. Lens plates or concentrating louvered reflectors may be built in a foot or two ahead of the vertical trim line, in either the soffit or floor of open display platforms or niches. Lamps of 100- to 200-watts will produce high lighting of 100 foot-candles or more on the display.

i. For extended vertical surface displays—rugs, tapestries, draperies, paintings—a series of 150- or 200-watt lens plate units at the ceiling is suitable for fixed display locations. Bracket-type parabolic, polished-metal troughs produce equivalent results and have some advantage in greater mobility.

j. Footlight-type trough lighting for counter and shelf displays ranges from single lumiline reflectors for counter cards and small displays to extended shelf troughs as illustrated. Trough footlights with changeable, luminous sign panels transform waste space into valuable display.

Fig. 9-10*f* to *j*.—Merchandise display. Spots and floods.



k. The problem in lighting mirror alcoves is to light the person and not the mirror. The sketch shows the use of a large aluminum ceiling reflector with a 500-watt silvered-bowl lamp; also louvered vertical trough reflectors with 40-watt clear or 60-watt daylight lamps on 6-in. centers.

l. Louvered spotlights with 150-watt lamps, located at the upper intersections of the mirrors offer a simple means of supplementary lighting; shown also is a plan for vertical recessed luminous elements built in at the edges of the three sections of mirror, and using 60-watt lumiline lamps.

m. Fitting-room mirrors entail the same requirements as other mirrors—the lighting emphasis may be obtained by louvered spots, built-in trough or lens plates, by luminous panels or louvered troughs. Where booths have white ceilings general illumination from indirect wall urns or indirect floor lamps will make the room more attractive.

n. Small vanity table mirrors require only a 60-watt white lumiline lamp in a portable reflector holder on each side of the mirror for acceptable lighting for millinery fitting. Larger vanity and dresser mirrors may have large built-in vertical panels.

o. Beauty-parlor booths present various lighting problems depending on the construction of the booth and the seeing task involved. The sketch shows a large area aluminum reflector with a 200- or 300-watt silvered-bowl lamp, adaptable as a low brightness source to individual open-top booths.

FIG. 9-10*k* to *o*. **Merchandise display. Mirrors and fitting rooms.**

p. Rug racks should be lighted as uniformly as possible from top to bottom. Concentrating units or parabolic trough reflectors with 150-watt lamps on 2-ft. centers will provide 30 to 50 foot-candles. Units should be aimed at the lower third of the rug.

q. For ready-to-wear displays it is desirable to secure fair uniformity both vertically and laterally and to provide from 50 to 100 foot-candles. Illumination of this order is necessary to perceive and to identify coloring, tints and textures and is equivalent to the daylight near a window or door. A parabolic metal trough 8 to 12 in. out from the cases with 60- to 100-watt standard lamps spaced 12 in. is a very satisfactory method.

r. For necessity and impulse items such as groceries, where attention rather than critical seeing is the requirement, less engineering refinement is needed in shelf lighting equipment. Concentrating trough reflectors which incorporate luminous panels for changeable advertising copy are satisfactory. Sockets 1 ft. apart may be lamped with 40- to 100-watt lamps, as conditions dictate.

s. For lighting displays on columns or built-in shelving a metal nosing along the front edge of each shelf effectively conceals small 25-watt tubular lamps as shown in the sketch. Lamps. should be spaced not more than 12 in. apart Lumiline lamps are, of course, equally suitable in many cases.

t. Displays of glassware and bottled goods are highly attractive and colorful if lighted by transmitted light as shown. An opal glass panel, illuminated uniformly from behind the lamps spaced not more than 1½ times their distance back of the glass will provide a suitable luminous background.

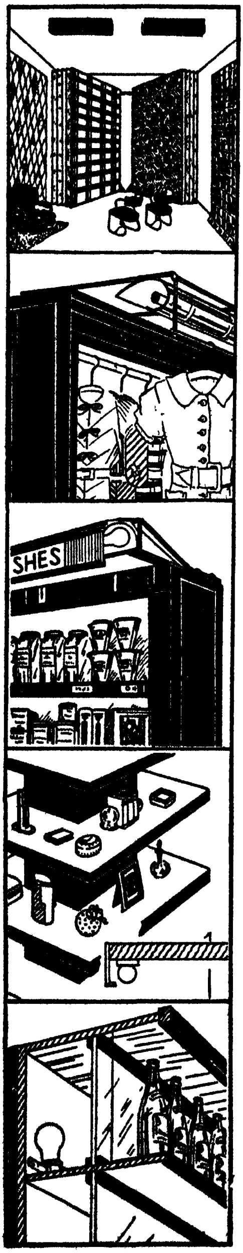


Fig. 9-10*p* to *t*. Merchandise display. Shelving and vertical displays.

Class C. 30 *to* 50 *Foot-candles.*—Necessary where visual tasks involve (1) moderately fine detail, (2) materials of average contrast, (3) critical seeing only intermittently.

Standard show-window equipment should be chosen to fit window dimensions and to concentrate light on the trim line.

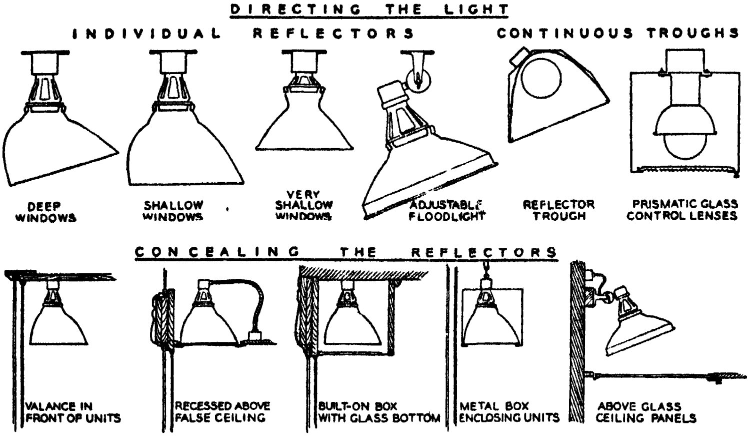

DIRECTING THE LIGHT
INDIVIDUAL REFLECTORS
CONTINUOUS TROUGHS
DEEP WINDOWS
SHALLOW WINDOWS
VERY SHALLOW WINDOWS
ADJUSTABLE FLOODLIGHT
REFLECTOR TROUGH
PRISMATIC GLASS CONTROL LENSES
CONCEALING THE REFLECTORS
VALANCE IN FRONT OF UNITS
RECESSED ABOVE FALSE CEILING
BUILT-ON BOX WITH GLASS BOTTOM
METAL BOX ENCLOSING UNITS
ABOVE GLASS CEILING PANELS

Fig. 9-11.—Show-window and display-case units.

Mirrored glass, polished metal, or prismatic units offer the control necessary to proper distribution. Reflectors should be concealed by valances or enclosed mounting. Louvers or

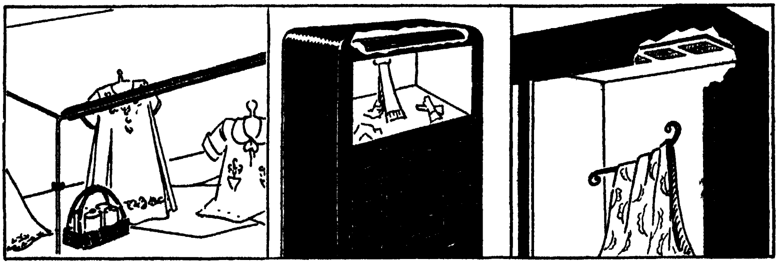


Fig. 9-12.—Display cases.

stippled-glass cover plates prevent glare where a row of units is exposed to the observer.

The better windows in brightly lighted districts use 300- and 500-watt units on 15- to 18-in. centers. At least 200-watt lamps on 12-in. centers will be required for downtown city stores;

a. Vertical surfaces, craneways, wash racks. Angle reflectors are often used in craneways and erecting shops, mounted below the crane rail, preferably 20 feet above floor, to supplement general overhead lighting and to build up the lighting on vertical surfaces. Used also to light individual machines, auto wash racks, and other operations that demand special distribution or direction of light. Special care is necessary in locating and shielding units to avoid their becoming glare sources to workers who face toward the units.

For fairly uniform lighting laterally along a vertical surface, such as a posterboard, the spacing between units should not exceed one and one-half times their distance out from the lighted surface.

b. Garages, hangars. Portable garage and repair standards are used for automotive repair work and critical inspection of parts. The usual extension cord equipped with 50- or 100-watt rough service Mazda lamps in a guard is indispensable for quick inspection and minor adjustments. Time-saver lighting in the form of two or more angle reflectors mounted on a heavy base or a portable rack is illustrated with outlets for electrical tools. The lighting units can be kept clean and efficient, harsh shadows are avoided; glare is eliminated; and the worker is free of the nuisance of interference and continual shifting of the unit to avoid shadows. Two hundred-watt units are recommended.

c Garages, roundhouses, service stations. Repair-pit and Auto-lift Lighting. The problem of lighting dark-colored undersurfaces of trucks, chassis, and body necessitates small equipments in sufficient number not only to give coverage but also to reduce shadows to a reasonable degree. Recessed angle reflectors with lens-type cover plates or special heavy-duty pit lighting equipment with prismatic covers and wire guards are used for automotive, trolley, and roundhouse repair pits. Units on 6- to 8-foot spacing on each side of the pit with 100- to 200-watt lamps recommended.

On auto lifts six units on each side of the wheel track with 50- or 100-watt rough service lamps in wire guards and upturned half-shade reflectors are quite satisfactory

d Auto assembly, body finishing, spray booths Special-purpose Projectors. Enclosed industrial projectors employing mercury or incandescent lamps find many applications in specialized lighting for many seeing tasks encountered in industry. The application illustrated shows the use of projector units with fluted cover glasses to spread a high level band of light on the vertical surfaces of an auto body for finishing and inspecting. With 300-watt units, equipped with spread lens and spaced 5 ft apart, the illumination on the working surface is of the order of 100 foot-candles A single 200-watt unit, without a spread lens, will provide about 200 foot-candles over an area of 7 to 8 sq. ft. at a distance of 5 ft.

e. Machine lighting, printing, proofreading, cloth products, woodworking. Louvered industrial spotlights to provide high level lighting over restricted areas where critical seeing demands from 50 to 250 foot-candles—encountered in thousands of applications in the machine tool, woodworking, printing and mechanical industries. Such units out of the way of the workmen will provide glare-free lighting but particular care must be exercised in their location so that confusing shadows are not introduced. A 150-watt unit will provide about 175 foot-candles at a 5-foot distance.

f. Machine lighting, sewing, cloth products, glove manufacturing, hat manufacturing, leather manufacturing, shoe manufacturing. Adjustable Local Lighting. Deep bowl porcelain-enameled or aluminum reflectors, with substantial supports, holders, and adjustment features, are suitable for intimate individualized purposes such as sewing machines, linotype, etc. Half-shade reflectors even though adjusted to the satisfaction of the operators are likely to be glaring to others.

Inside-frosted lamps of 25 to 60 watts will provide 50 to 150 foot-candles at a distance of 6 in. For many purposes, *e.g.*, sewing, Daylight lamps are being used because of the whiter quality of light.

g. Paintshops, refineries, flour mills. Vaporproof and Explosion-proof Equipments. Designed for locations where corrosive vapor, inflammable gases or explosive dusts are likely to be encountered. In moisture-laden atmospheres such as steam processing, engine rooms, shower baths, and also where gases and vapors from such processes as oil refining, paint and varnish making, spray lacquer painting, units of this character are recommended. Mandatory requirements are covered in detail in the National Electrical Code.

The sketch shows the application of vaporproof equipment in a spray paint booth. Equipments include both angle and symmetrical types of reflectors in the range from 75- to 500-watt sizes.

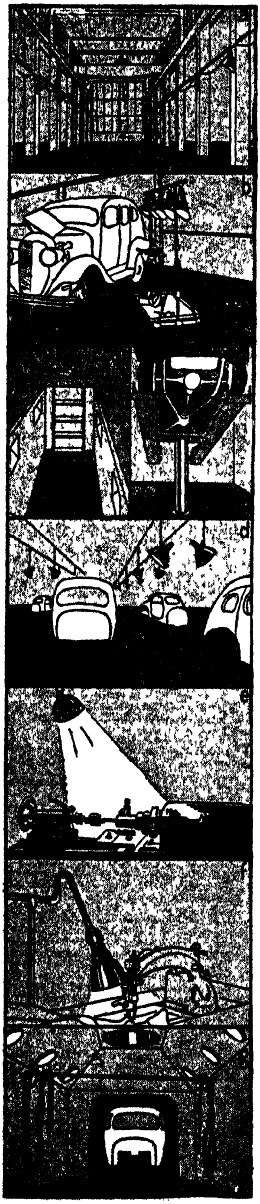
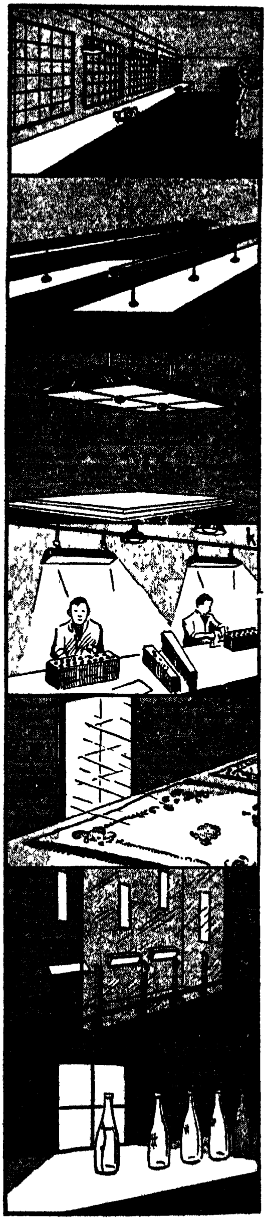


Fig. 9-13*a*–*g*.—Industrial applications



h. Bench and Inspection Lighting. General lighting alone will not usually be adequate for benchwork requiring critical detailed seeing necessary in fine processing, assembly, or inspection. R.L.M. dome or deep bowl porcelain-enameled reflectors can be spaced one and one-half times the mounting height above the bench. At a 3-ft. mounting, 150-watt inside-frosted lamps will produce 60 foot-candles; 200-watt lamps, 90 foot-candles. R.L.M. domes with white bowl lamps, Glassteel diffusers, or trough sections (see *i*, *j*, *k*) with diffusing glass coverplate are recommended where seeing task requires avoidance of specular reflection and harsh shadows. Parabolic, louvered concentrating single units or continuous parabolic trough sections with silvered-bowl lamps are recommended particularly at higher mounting heights, in order to produce a uniform, high-level band of illumination along the bench. From 50 to 100 foot-candles or more is required, depending on the fineness of the task.

i. Assembly and Inspection-table Lighting. In many industrial operations, work positions are fixed and materials flow on belts or conveyers in front of operators for processing, labeling, assembly, or inspection. In many instances continuous diffusing or concentrating sources of illumination offer a good solution, though each job requires analysis and modification to meet specific requirements. With the light source at eye level or below direct glare is eliminated. Where the material or operation does not introduce glaring reflections open-type, continuous troughs are satisfactory; where shiny or polished material is present a diffusing reflector or diffusing glass cover panel should be used In some instances duplicate facilities must be provided: (1) diffuse lighting for certain defects, and (2) directional lighting or glint which may be essential to reveal others.

j. Engraving, printing, lithographing, jewelry and watch manufacturing, sheet-metal inspection. Large-area Diffusing Sources Large-area sources of low surface brightness and good diffusion are necessary for assembly and inspection where the work surfaces or parts of it are shiny, such as the freshly cast type on the printer's imposing stone illustrated. Large diffusing sources minimize obscuring reflections, and the illumination on the work may be built up to high values without uncomfortable brightness. A painted metal or matte porcelain reflecting housing using neck-frosted silvered-bowl lamps and a frosted cover glass may be used. Similar construction is likewise satisfactory in many instances when used in a vertical position to simulate direction and qualty of normal window lighting.

k. Fine assembly, inspection, grinding, polishing, glass inspection. Diffusing-trough Units. Small trough units of porcelain enamel with diffusing cover glass find much application in lighting extended surfaces such as on shearing and cutting machines, carpet looms, and printing presses where a uniform band of light is required. Space limitations often dictate the design of the unit and type of lamp used; standard units are listed in equipment catalogues.

Open or louvered troughs may be used where the materials lighted are in themselves diffusing, but where specular materials or machine parts are encountered the light should be diffused at the source.

l. Inspection. Directional Light. Surface flaws, irregularities in surface shape, pit marks, scratches and cracks in materials are most easily seen by lighting which strikes the surface obliquely, casting a shadow and revealing the irregularities by shadow contrast. Thus unevenness in the nap of carpet or cloth is revealed by small shadows emphasized by a sharp directional light. The light may be undiffused for diffusing materials but diffused at the source for polished or shiny materials; thus ball bearings, pistons, valve stems, etc., may be examined for flaws by viewing them on a luminous glass panel.

m. Inspection. Transmitted Light. Open-weave fabrics, porous and translucent materials, such as glass, paper plastics, and liquids will reveal certain kinds of faults and defects by transmitted light. Large luminous panels of diffusing glass may be built in conveyer lines over which the material flows, or luminous vertical panels may be used as artificial windows against which such materials may be viewed.

n. Inspection. Refraction. Refractive materials, such as plate glass, bottles, bulbs, etc., when viewed against a luminous background will reveal bubbles, blisters, cracks, chips and whorls by high lights or distortions. Alternating the observation between dark and luminous backgrounds introduces movement which aids in locating and identifying defects.

Similarly surface distortions and irregularities in polished sheet metal or window glass are revealed by the distortion of reflected images of straight-lined bars or strips laid on the luminous background.

FIGS. 9-13*h*–*n*.—Industrial applications.

150-watt lamps for secondary business districts; 75- or 100-watt lamps for neighborhood stores and small towns.

Recommended foot-candle standards serve principally as a relative gauge of requirement for different localities. Adjacent displays, traffic exposure, color, type, and arrangement of merchandise and background are also prime factors in window effectiveness and emphasis.

Showcases and wall cases require from two to four times as many foot-candles as the general illumination throughout the store if they are to stand out prominently and command attention. Standard showcase equipment is available for tubular bulb and lumiline lamps and in individual mirrored reflectors taking the class *A* bulb lamps.

A common shortcoming in the lighting of wall cases is the use of wide distribution reflectors which fail to concentrate the light on the merchandise display but produce predominant and oftentimes distracting light on the upper background. Small compact parabolic aluminum trough reflectors or other concentrating distribution units are best applied in most cases.

Large shallow cases may often best be lighted by a row of concentrating prismatic lens plates built in the top of the case.

From 40 to 60 watts per running foot of showcase will be required to supply 50 to 100 foot-candles along a normal curve of trim.

Properties of Paints.—The results of tests of 26 types of white paint are shown in Table 9-11.[1] The test was conducted for 20 months. Samples of the painted surfaces were kept both in glass-covered cabinets and in exposed factory conditions. It was found that the average initial reflection factor was 81.1 per cent. The maximum value found was 87.6 per cent for a flat paint with titanox, lead and free zinc as pigment material. While the minimum reflection factor was 75.5 per cent for a flat paint with lithopone as the pigment. By groups those paints having titanox as part of the pigment had the highest initial reflection factor, with those of lithopone, lead, and zinc following in order. The rate of depreciation is in the same order also as shown in Figs. 9-14 and 9-15.

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[1] *J. Am. Inst. Elec. Eng.*, February, 1926, p. 188; *Bull.* LD-101-B, Edison Lamp Works, General Electric Company.

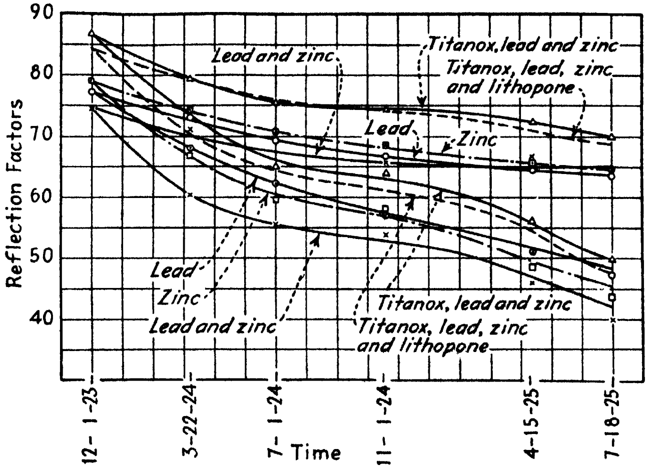

FIG. 9-14.—Average depreciation curves of paints of various components as indicated, applied to wood, concrete and metal surfaces. In each instance the upper set of curves shows the rate of depreciation of samples enclosed in a glass cabinet exposed to the light, but protected from dust.

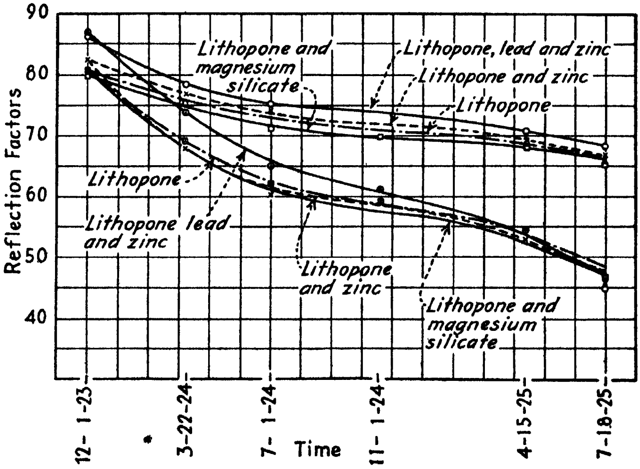

FIG. 9-15.—Average depreciation curves of paints of various components as indicated, applied to wood, concrete and metal surfaces. In each instance the upper set of curves shows the rate of depreciation of samples enclosed in a glass cabinet exposed to the light, but protected from dust.

TABLE 9-11.—PROPERTIES OF WHITE PAINT

Specimen No.	Basic pigment	Type of finish	Initial reflection factor	Average reflection factor during 20 months		Appearance at end of test
				Cabinet set	Factory set	
1	Lithopone, zinc oxide	Undercoat Semi-gloss	81.9	73.1	64.7	Grayish
2	Zinc oxide, lithopone	Eggshell	82.5	71.3	62.0	White
3	Titanox, lead, zinc	Flat white	86.9	76.3	65.7	White
4	Lithopone, lead, zinc	Gloss	86.6	75.3	63.5	Bluish
5	Lithopone, titanox, lead zinc	Eggshell	84.3	75.3	63.2	White
6	Zinc oxide, lithopone	Flat white	85.2	76.4	64.3	White
7	Zinc oxide, lithopone	Gloss	83.7	74.8	57.6	Bluish
10	Lithopone	Enamel	80.4	73.75	57.9	White
11	Lithopone	Flat white	82.7	75.9	61.8	Cream
12	Lithopone, zinc oxide	Gloss	81.8	74.5	59.15	White
13	Lithopone	Eggshell	81.7	74.4	61.8	Cream
15	Lithopone	Flat white	81.7	74.8	60.9	White
16	Lithopone	Gloss	82.2	74.8	61.1	White
17	Lithopone	Semi-gloss	78.5	72.8	60.6	Cream
18	Zinc oxide	Semi-gloss	75.8	68.8	57.2	White
20	Lithopone	Flat white	75.3	68.0	59.2	White
21	Lithopone	Eggshell	79.75	69.4	58.3	White
22	Lithopone	Gloss	77.4	68.7	52.9	Cream
24	White lead	Flat white	77.25	68.5	59.8	White
27	Zinc oxide	Enamel	83.5	65.8	59.65	White
29	Lead, zinc oxide	Eggshell	75.1	68.3	55.5	Cream
30	Lithopone, magnesium silicate	Eggshell	80.0	70.7	60.7	White
32	Lithopone, zinc oxide	Gloss	80.1	73.8	61.5	White
33	Lithopone, magnesium silicate	Flat white	80.0	72.5	62.2	White
34	Lithopone	Eggshell	81.4	73.5	61.7	White
35	Lithopone	Gloss	82.1	73.6	63.2	Grayish

It is rather difficult to tabulate the *reflection factors* for various colors. A number of elements create this condition. There is no standard terminology of paint colors. A tint which one manufacturer may call ivory tan may be quite different in appearance and in reflecting properties from some other maker's color under the same name. The chemical composition or the method of mixing the paint will have an effect on its ability to reflect light. A higher or lower oil content, *e.g.*, produces slight variation.

The most feasible means of presenting the necessary data seems to be to tabulate a number of commonly used colors under a rather broad classification and give a range in percentage of reflection for any particular color.

The figures presented in Table 9-12 are the results of a considerable number of tests and are representative average values.

TABLE 9-12.—REFLECTION FROM PAINTED SURFACES*

Color	Reflection, per cent	Color	Reflection, per cent
Flat white	75 to 85	Spanish or bright orange	35 to 40
Gloss white	75 to 80	Medium brown	25 to 35
Cream	65 to 75	Dark gray	20 to 25
Bright yellow	60 to 70	Cardinal or dark red	20 to 25
Aluminum paint	60 to 65	Willow or medium green	15 to 25
Buff	52 to 56	Olive green	12 to 15
Very light blue	45 to 55	Dark brown	8 to 10
Apple or pale green	40 to 55	Spanish or bright blue	5 to 10
Light gray†	35 to 50		

* *Am. Architect*, Am. Inst. Architects, File No. 31-F.

† Grays vary remarkably, depending on the way they are prepared. A gray made by mixing lampblack with white paint has a low coefficient of reflection. A gray made by mixing red and green paint with a white base has a relatively high coefficient of reflection and is known as a warm gray.

Wiring Specifications.[1]—The National Electrical Code regulations are intended to insure protection from fire hazards but will not necessarily provide a wire size sufficient for the most efficient use of lamps and equipment, nor do they make provision for future increases of energy for illumination. Wires should be of sufficient size not only to allow lamps to operate at normal voltage but to provide for future requirements, since the trend of illumination intensities is ever upward. The cost of rewiring finished buildings is much greater and often many times greater than the additional cost of providing capacity for future requirements in the original installation.

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[1] "Industrial Lighting Code," *Illum. Eng. Soc.*, vol. 25, p. 611, 1930.

TABLE 9-13.—REFLECTION FACTORS OF VARIOUS MATERIALS AND SURFACES*

Material	Reflection factor, per cent	Material	Reflection factor, per cent
White plaster	90 to 95	Polished gold	50 to 55
Polished silver	90 to 92	Alabaster veined	49 to 67
Alzak	85	Monel metal	49 to 55
White blotting paper	82	Limestone	35 to 58
White cartridge paper	80	Polished marble	30 to 70
Oxidized or etched aluminum	70 to 89	Tracing cloth	30
Mirrors, silvered	70 to 85	Impregnated marble	27 to 54
Highly polished brass	70 to 75	Colored alabaster	27 to 29
Ordinary foolscap	70	Light oak finish	25 to 35
Glazed white porcelain enamel	65 to 77	Gray cement	20 to 30
Matte white porcelain enamel	60 to 83	Granite	20 to 25
Chromium	63 to 66	Macadam road	12
Polished aluminum	62	Red brick	10 to 15
Terra cotta, white and cream, smooth and matte	60 to 80	Dark oak finish	10 to 15
		Mahogany finish	6 to 12
Speculum metal	60 to 80	Walnut finish	5 to 10
Highly polished copper	60 to 70	Black paper	5
Aluminum paint	60 to 65	Black cloth	1.2
Highly polished steel	60	Dead-black paint	1
Caen stone	55 to 65	Black velvet	0.4
Chromium-nickel (stainless) steel	55		

* *Am. Architect*, November, 1934 (Am. Inst. Architects, File No. 31-F).

Specifications by the National Electric Light Association supplement the code in making reasonable provisions for economical distribution of energy and the probable lighting requirements of the future. Accordingly a single branch circuit should not supply the overhead lighting for a work space greater than 400 sq. ft. or more than 800 sq. ft. of hall passageway or nonproductive area. The initial *load* on a single circuit should not exceed 1,000 watts except in case of a single lamp of larger size. The smallest size wire should be No. 12 gauge, and from panel to the first outlet of from 50 to 100 ft. No. 10 wire should be the smallest, with No. 12 wire between outlets. Runs of more than 100 ft. from the panel board should be avoided either by relocation or by additional panel boards.

TABLE 9-14.—TRANSMISSION, REFLECTION, AND ABSORPTION FACTORS FOR TYPICAL TRANSLUCENT MATERIALS*

Type	Thickness, inches	Transmission, per cent	Reflection, per cent	Absorption, per cent
Clear glass		80 to 92	8 to 10	2 to 10
Silvered			82 to 93	7 to 18
Configurated, obscure†	0.12 to 0.23	57 to 90	7 to 24	3 to 21
Satin finish:†				
Toward source	0.075	89	8	3
Away from source	0.075	85 to 88	6 to 8	4 to 9
Acid etched:†				
Toward source	0.08	82 to 88	7 to 9	5 to 10
Away from source	0.08	63 to 78	12 to 20	10 to 17
Sandblasted:†				
Toward source	0.08 to 0.12	77 to 81	11 to 16	7 to 11
Away from source	0.08 to 0.12	70 to 77	13 to 18	10 to 16
Alabaster glass	0.125 to 0.19	60 to 70	20 to 30	10
Other opalescent glasses†	0.09	58 to 84	13 to 18	2 to 14
Marble ($CaCO_3$):†				
One side polished	0.29 to 0.39	3 to 8	30 to 71	24 to 65
Impregnated	0.12 to 0.20	12 to 40	27 to 54	11 to 49
Alabaster ($CaSO_4$):†				
Veined	0.44 to 0.53	17 to 30	49 to 67	14 to 21
Colored	0.25	34 to 50	27 to 29	21 to 39
White ceramic-coated clear glass, varying diffusion	0.125	40 to 64	24 to 50	10 to 13
Flashed opal glass:†				
Group 1	0.08 to 0.11	47 to 66	31 to 45	3 to 10
Group 2	0.11 to 0.13	27 to 35	54 to 67	8 to 11
Composition material:				
White diffusing	0.010 to 0.025	0 to 41	32 to 75	7 to 27
Clear matte, typical sample	0.010	68	15	17
Solid opal glass:†				
Group 1	0.07 to 0.14	12 to 38	40 to 66	20 to 31
Group 2	0.07 to 0.10	37 to 51	43 to 54	6 to 11
Group 3	0.06 to 0.14	13 to 35	65 to 78	4 to 10

* POTTER and MEAKER, "Luminous Architectural Elements," *Trans. Illum. Eng. Soc.*, vol. 26, p. 1025, 1931.

† E. SUMMERER, "Lichttechnische Baustoffe," *Lichtheft* S-8, Osram Company, Berlin.

Where distances of 100 ft. cannot be avoided, the lamp load should be limited to 600 watts for each branch circuit. Convenience outlets should be placed on separate circuits. The outlets should be of the duplex type and not more than six on a circuit.

The wire not less than No. 12 for runs less than 100 ft. and No. 10 wire where the runs must be longer.

Panel boards should contain one spare circuit position to each five active circuits. It is generally desirable to supply each circuit position with a switch. At least one panel board should be provided for each floor of a building and so located that branch circuit runs exceeding 100 ft. to the first outlet can be avoided.

Feeders should be of such size that the voltage drop from the service switch to the panel board will not exceed 1.5 per cent with a load of lamps (115 volts) on every branch circuit which it supplies.

Conduits for enclosing feeders should be of sufficient size to permit replacing the original feeders with standard-gauge wires two sizes larger.

In the following paragraphs are wiring recommendations based upon modern practice.

Branch Circuits for General Illumination.—Maximum drop panel board to outlets 2 volts.

Load and Length of Run.—For 15-amp. circuits the initial load per circuit should not exceed 1,000 watts, with No. 12 minimum wire size to be used where length of run does not exceed 50 ft.; No. 10 wire for runs of 50 to 100 ft.; No. 8 wire for runs of 100 to 150 ft.

For heavy-duty lamp circuits (the National Electrical Code permits 8 mogul sockets, 40 amp. per circuit) 3,000 watts with No. 8 wire for up to 50 ft. runs; No. 6 wire for 50 to 100-ft. runs; No. 4 wire for runs from 100 to 150 ft. It is recommended that panel boards be so located that the length of run does not exceed 100 ft., if practical to do so.

Panel Boards.—One spare circuit should be provided for each five circuits used in the initial installation. Concealed branch circuit conduit should be large enough for one additional circuit for every five or less circuits it contains.

Service and Feeders.—Maximum feeder drop 2 volts. The carrying capacity of service wiring and feeders should be sufficient for the normal branch circuit load with no more than a 2-volt drop. Normal diversity of branch circuit load in many cases reduces required feeder capacity below the actual total branch circuit load; the National Electrical Code allowances for this demand factor should govern. Provision should be made for increasing feeder capacity to take care of next larger lamp size (50 per cent increase) than installed initially.

Convenience Outlets for Lighting.—Should not be connected to branch circuits which supply fixture outlets as a part of the general illumination system. No wire smaller than No. 12 should be used; No. 10 if the length of run exceeds 100 ft.

In *office space* there should be one convenience outlet circuit for each 800 sq. ft. of floor area with at least one duplex outlet for each 20 linear feet of wall.

In manufacturing spaces there should be one convenience outlet for each 1,200 sq. ft. or fraction of floor space with at least one duplex outlet in each bay.

In stores there should be at least one convenience outlet in each supporting column or at least one floor outlet for each 400 sq. ft. or fraction of floor space. For windows at least one outlet for each 5 linear feet of plate glass, with an additional floor outlet for each 50 sq. ft. of platform area. Provision for sign should be made by installing a 1-in. conduit from the distribution panel to the front face of the building for each individual store space.

For convenience and for illustration the sizes of wires computed for various loads and distances from panel box to load center are given in Table 9-15.

Switches.—Switches for controlling the lamps in a room should be located near the entrance. If there are several entrances to a room a switch controlling at least one circuit of lamps should be located at each entrance, better three- or four-way switches. In large interiors a symmetrical arrangement of switches in convenient places will greatly simplify the finding of switches or control devices.

A group of lamps may occupy a bay or square or they may be in rows parallel to the windows. When grouped in squares the benefit of several near-by lamps will be secured. When grouped in rows those farthest from the windows may be turned on when needed, with greater effectiveness and economy.

Where large groups of lights involving several circuits are controlled at the same time, it may be most economical to employ a remote-control switch placed wherever wiring economy dictates, which is operated in turn by a momentary-contact button at the point of most convenient access. The use of remote-control switches makes it unnecessary to carry large wire sizes to wall switches, thereby often saving more than the cost of the remote-control apparatus in materials and line losses.

Automatic control of light has been made possible by the development of photoelectric-cell relay equipment which responds to prevailing illumination in any given space. This light-sensitive element will turn on artificial lights wherever natural lighting diminishes below the desired minimum level of illumination. The lights remain on until turned off manually or by a time switch, or until natural light increases the level of illumination sufficiently to dispense with the artificial sources.

Where graduated illumination is required as in auditoriums, dance halls, theaters, etc., it is preferable to use alternating current and reactance dimming because it is much more efficient than old-style resistance dimming. The new thyratron control

TABLE 9-15.—WIRE SIZE REQUIRED*

Computed for maximum of 2-volt drop on two-wire, 120-volt circuits

Load per circuit, watts	Current, amperes	Length of run, panel box to load center, feet																	
		30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
500	4.2	14	14	14	14	14	14	12	12	12	12	12	12	10	10	10	10	10	10
600	5.0	14	14	14	14	14	12	12	12	12	10	10	10	10	10	10	10	8	8
700	5.8	14	14	14	14	12	12	12	10	10	10	10	10	10	8	8	8	8	8
800	6.7	14	14	14	12	12	12	10	10	10	10	10	8	8	8	8	8	8	8
900	7.5	14	14	12	12	12	10	10	10	10	8	8	8	8	8	8	8	8	6
1,000	8.3	14	14	12	12	10	10	10	10	10	8	8	8	8	8	8	6	6	6
1,200	10.0	14	12	12	10	10	10	10	8	8	8	8	8	6	6	6	6	6	6
1,400	11.7	14	12	10	10	10	8	8	8	8	8	6	6	6	6	6	6	6	6
1,600	13.3	12	12	10	10	8	8	8	8	6	6	6	6	6	6	6	6	4	4
1,800	15.0	12	10	10	10	8	8	8	6	6	6	6	6	6	4	4	4	4	4
2,000	16.7	12	10	10	8	8	8	6	6	6	6	6	6	4	4	4	4	4	4
2,200	18.3	12	10	10	8	8	8	6	6	6	6	6	4	4	4	4	4	4	2
2,400	20.0	10	10	8	8	8	6	6	6	6	6	4	4	4	4	4	4	2	2
2,600	21.7	10	10	8	8	6	6	6	6	4	4	4	4	4	4	4	4	2	2
2,800	23.3	10	8	8	8	6	6	6	6	4	4	4	4	4	4	4	2	2	2
3,000	25.0	10	8	8	6	6	6	6	6	4	4	4	4	4	4	2	2	2	2
3,500	29.2	10	8	8	6	6	6	4	4	4	4	2	2	2	2	2	2	2	2
4,000	33.3	8	8	6	6	6	4	4	4	4	2	2	2	2	2	2	1	1	1
4,500	37.5	8	6	6	6	4	4	4	2	2	2	2	2	2	1	1	1	1	1

* WARD HARRISON and C. E. WEITZ, Illumination Design Data, LD-6A, Nela Park Eng. Dept., General Electric Company, 1936.

combined with reactors permits the most delicate effects and the finest graduations.

The special wiring devices which add materially to the convenience of the installation are many. Among them might be mentioned:

The switch handle or small indicator on a pull-chain socket provided with luminous material which glows in the dark, making it possible to locate the control readily.

TABLE 9-16.—DIMENSIONS, WEIGHTS, AND RESISTANCES OF PURE COPPER WIRE

Brown and Sharpe Gauge

Gauge No.	Diam., in.	Area	Weight		Length	Resistance at 75°F.			Carrying capacities, amperes	
		Circular mils (d^2) 1 mil = 0.001 in.	Lb. per mile	Lb. per 1,000 feet	Feet per pound	Length, feet per ohm	R ohms per 1,000 ft.	Ohms per pound	Rub. ins.	Other ins.
*	1.152	1000000	16165.	3050.	0.3250	95100.	0.01051	0.000003442	650	1000
*	1.035	800000	12932.	2440.	0 4170	76100.	0.01313	0 000005380	550	840
*	0.963	700000.	11315.5	2135.	0.4680	66600.	0 01501	0.000007030	500	760
*	0.891	600000.	9699.	1830.	0.5460	57100	0.01751	0 000009579	450	680
*	0.819	500000.	8082.5	1525.	0.6550	47500.	0.02101	0.00001376	400	600
*	0.728	400000.	6466.	1220.	0.8200	38050.	0.02627	0.00002155	325	500
*	0.590	250000.	4038.6	762.	1.32	23750.	0.04203	0 00005600	240	350
0000	0.4600	211600.	3375.66	639.3	1.56	20383.	0.04906	0.00007673	225	325
000	0.4096	167805.	2677.01	507.0	1.97	16165.	0 06186	0 00012039	175	275
00	0.3648	133079.	2123.03	402.0	2.49	12820.	0 07801	0.00019423	150	225
0	0.3248	105538.	1683.58	318.8	3.14	10166.	0 09838	0.00038500	125	200
1	0.2893	83694.	1335.21	252.8	3.99	8062.3	0 12404	0.00048994	100	150
2	0.2576	66373.	1058.85	200.5	4.99	6393.7	0.15640	0.00078045	90	125
3	0 2294	52634	839.68	159.0	6.29	5070.2	0.19723	0.0012406	80	100
4	0.2043	41742.	665.91	126.1	7.93	4021.0	0.24869	0 0019721	70	90
5	0.1819	33102	528.05	100 0	10.00	3188.7	0.31361	0.0031361	55	80
6	0.1620	26250.	418.81	79.32	12.61	2528.7	0.39546	0.0049868	50	70
7	0.1442	20816	332.11	62.90	15.90	2005.2	0.49871	0.0079294	38	54
8	0.1284	16509.	263 37	49.88	20.05	1590.3	0.62881	0.012608	35	50
9	0.1144	13094.	208.88	39.56	25.28	1261.3	0.79281	0.020042	28	38
10	0.1018	10381.	165.63	31.37	31.38	1000.0	1.	0.031380	25	30
11	0.0907	8234.	131.37	24.88	40.20	793.18	1.2607	0.050682	23	27
12	0.0808	6529.	104.17	19.73	50.69	629.02	1.5898	0.080585	20	25
13	0.0719	5178.	82.63	15.65	63.91	498.83	2.0047	0.12841	17	23
14	0.0640	4106.	65.68	12.44	80.38	395.60	2.5278	0.20322	15	20
15	0.0570	3256.	51.96	9.84	101.63	321.02	3.1150	0.31658		
16	0.0508	2582.	41.24	7.81	128.14	248.81	4.0191	0.51501	6	10
17	0.0452	2048.	32.68	6.19	161.59	197.30	5.0683	0.81900		
18	0.0403	1624.	25.92	4.91	203.76	156.47	6.3911	1.3023	3	5

TABLE 9-17.—ELECTRIAL SYMBOLS FOR ARCHITECTURAL PLANS

GENERAL OUTLETS

Ceiling	Wall	
○	-○	Outlet.
Ⓒ	-Ⓒ	Capped outlet.
Ⓓ		Drop cord.
Ⓔ	-Ⓔ	Electrical outlet—for use only when circle used alone might be confused with columns, plumbing symbols, etc.
Ⓕ	-Ⓕ	Fan outlet.
Ⓙ	-Ⓙ	Junction box.
Ⓛ	-Ⓛ	Lamp holder.
Ⓛ FS	-Ⓛ FS	Lamp holder with pull switch.
Ⓢ	-Ⓢ	Pull switch.
Ⓥ	-Ⓥ	Outlet for vapor-discharge lamp.
Ⓧ	-Ⓧ	Exit light outlet.
◷	-◷	Clock outlet (lighting voltage).

CONVENIENCE OUTLETS

=⊖	Duplex convenience outlet.
=⊖ 1,3	Convenience outlet other than duplex. 1 = single, 3 = triplex, etc.
=⊖ WP	Weatherproof convenience outlet.
≡⊖ R	Range outlet.
=⊖-$	Switch and convenience outlet.
=⊖-[R]	Radio and convenience outlet.
⬤	Special-purpose outlet (describe in specifications.)
◉	Floor outlet.

SWITCH OUTLETS

$	Single-pole switch.
$$\$_2$$	Double-pole switch.
$$\$_3$$	Three-way switch.
$$\$_4$$	Four-way switch.
$$\$_D$$	Automatic door switch.
$$\$_E$$	Electrolier switch.
$$\$_K$$	Key-operated switch.
$$\$_P$$	Switch and pilot lamp.
$$\$_{CB}$$	Circuit breaker.
$$\$_{WCB}$$	Weatherproof circuit breaker.
$$\$_{MC}$$	Momentary contact switch.
$$\$_{RC}$$	Remote-control switch.
$$\$_{WP}$$	Weatherproof switch.

SPECIAL OUTLETS

○ a,b,c-etc. =⊖ a,b,c-etc $ a,b,c-etc.	Any standard symbol as given above with the addition of a lower case subscript letter may be used to designate some special variation of standard equipment of particular interest in a specific set of architectural plans. When used they must be listed in the Key of Symbols on each drawing and, if necessary, further described in the specifications.

PANELS, CIRCUITS, AND MISCELLANEOUS

▬	Lighting panel.
▨	Power panel.

PANELS, CIRCUITS, AND MISCELLANEOUS.—(*Continued*)

——	Branch circuit—ceiling or wall.
- - -	Branch circuit—floor. *Note:* Any circuit without further designation indicates a two-wire circuit. For a greater number of wires indicate as follows: —///— (3 wires), —//——//— (4 wires), etc.
━━━	Feeders. *Note:* Use heavy lines and designate by number corresponding to listing in feeder schedule.
≡□≡	Underfloor duct and junction box—triple system. *Note:* For double or single systems, eliminate one or two lines. This symbol is equally adaptable to auxiliary system layouts.
Ⓖ	Generator.
Ⓜ	Motor.
Ⓘ	Instrument.
Ⓣ	Transformer.
⊠	Controller.
[S]	Isolating switch.

AUXILIARY SYSTEMS

⊡	Push button.
□/	Buzzer.
□○	Bell.
-◇	Annunciator.
◁	Telephone.
□◁	Telephone switchboard.
[◷]	Clock (low voltage).
[D]	Electric door opener.
[F]○	Fire-alarm bell.
[F]	Fire-alarm station.
☒	City fire-alarm station.
[FA]	Fire-alarm central station.
[FS]	Automatic fire-alarm device.
[W]	Watchman's station.
[[W]]	Watchman's central station.
[H]	Horn.
[N]	Nurse's signal plug.
[M]	Maid's signal plug.
[R]	Radio outlet.
[[SC]]	Signal central station.
▭	Interconnection box.
ǀǁǀǁǀǁ	Battery.
—·—·—	Auxiliary system circuits. *Note:* Any line without further designation indicates a two-wire circuit. For a greater number of wires, designate with numerals in manner similar to —-— 12-No. 18W-¾″-C., or designate by number corresponding to listing in schedule.
□ a,t	**SPECIAL AUXILIARY OUTLETS** *Note:* Subscript letters refer to notes on plans or detailed description in specifications.

Switches with small lamps concealed in their mechanism which serve to indicate that the attic or cellar lights are burning. Buzzing devices serve the same purpose.

Switches which can be attached to the ceiling or concealed in a canopy where wall switches are missing and it is not deemed advisable to do any extensive wiring.

Three-way switches for controlling the light from two points.

Two or more circuit switches in one mechanism to produce various degrees of lighting by pushing or turning the button a certain number of times.

Switches which operate automatically when a closet door is opened or closed.

Master switches for lighting the whole house from the owner's bedside in case of emergency.

Convenience receptacles which can be installed in the wall, baseboard, floor, or under a table. These should be of the standard type to take a plug with ¼-in. parallel blades spaced ½ in. apart so that all plugs are interchangeable.

Bell-ringing transformers which do away with maintaining batteries for this purpose.

In Tables 9-16 and 9-17 are given data on copper wire and a set of standard symbols for wiring plans as adopted and recommended by the National Electrical Contractors' Association of the United States and the American Institute of Architects.

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CHAPTER X

MODERN LIGHTING[1]

A decade ago practically all interior lighting by electricity used fixtures of either direct, semi-indirect, or totally indirect type. Today these three kinds of light sources have been supplemented by panel and cove lighting, column, pilaster and beam lights, luminous light boxes, niches and coffers, spotlights and downlights. The ordinary incandescent lamp has found new forms and greater adaptability, and three types of gas-filled tubular light sources have entered the field bringing color as an added tool for those who would "design in light."

These advances have accompanied a wholly new trend in lighting with new and better concepts and standards of interior artificial illumination. They enable the architect to provide light according to mood as well as need. They free him utterly from the past domination of the light fixture as a major element in his interior designs: now he can subordinate the light source to the things to be seen.

It is the architect's opportunity—and in truth, his obligation—to design building interiors for nighttime effect as well as day. The amateur selection of light sources, brought about by leaving their choice largely to the client as a last-minute decision, has ruined too many good projects to permit its continuance. Light and shade have always been an essential part of an architectural composition; why should the daytime aspect be spoiled at night by inept, if not actually bad, artificial lighting?

Moreover, the architect's relation to lighting is further established when it is fully appreciated that both initial cost and operating cost of proper lighting are directly related to the color, texture, and surface finish employed on walls, ceilings, floors, and even the furnishings of any room. If *efficiency* is the primary objective in lighting design the choice of surface treatments is relatively limited. If *appearance*, including styling or decorative treatment, is the first consideration, the choice of light sources and their disposition is largely governed by the selected colors, textures, and contrasts to be illuminated.

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[1] Much of the material in the first part of this chapter came from the *American Architect*, November and December, 1934, Am. Inst. Architects File No. 31-F.

Many elements employed in modern lighting involve no special dimensional or planning considerations other than proper spacing and capacity of outlets that serve them. In this category fall luminaires, droplights, portable floor and table lamps, and decorative ceiling fixtures and wall brackets. In this group also belong many new "fixtures," developed within the last year or two by progressive manufacturers, in which the traditional character and eye appeal of the ornamental chandelier and wall bracket have been blended successfully with reflectors and refractors that conform to modern concepts of good lighting.

Such units deserve special consideration in any study of interior illumination because they satisfy the normal desire to see the source of light; they retain the values inherent in the tradition of the flame as a light source; they have unlimited decorative possibilities; and they can provide almost any desired illumination level without glare and under complete control. They represent also, a logical and economical way of modernizing the lighting of interiors by merely taking the place of inadequate and glare-producing fixtures without expensive reconstruction for new outlets or built-in sources.

Light sources that are built into the structure affect preliminary planning and usually require special detailing on architect's drawings. Performance characteristics, design limitations, and space requirements of these less familiar light sources follow:

Cove lighting requires a fairly high ceiling free of beams and other obstructions. The side wall or ceiling close to the light source should be vertical or nearly so; the maximum rise should be at the center of the ceiling, but an arc of a circle is not desirable as the lamps produce a spotty effect at the cove. The narrower the room the easier it is to secure uniform lighting.

Coves should be above eye height and must be accessible for relamping and cleaning. They should be sufficiently below the ceiling to give the light a chance to "spread" and thus avoid spottiness. See Fig. 10-1 for recommended design practice. Unless the cove is covered with dust-tight glass plaster should not be used to form the reflecting trough behind the lamps, as it

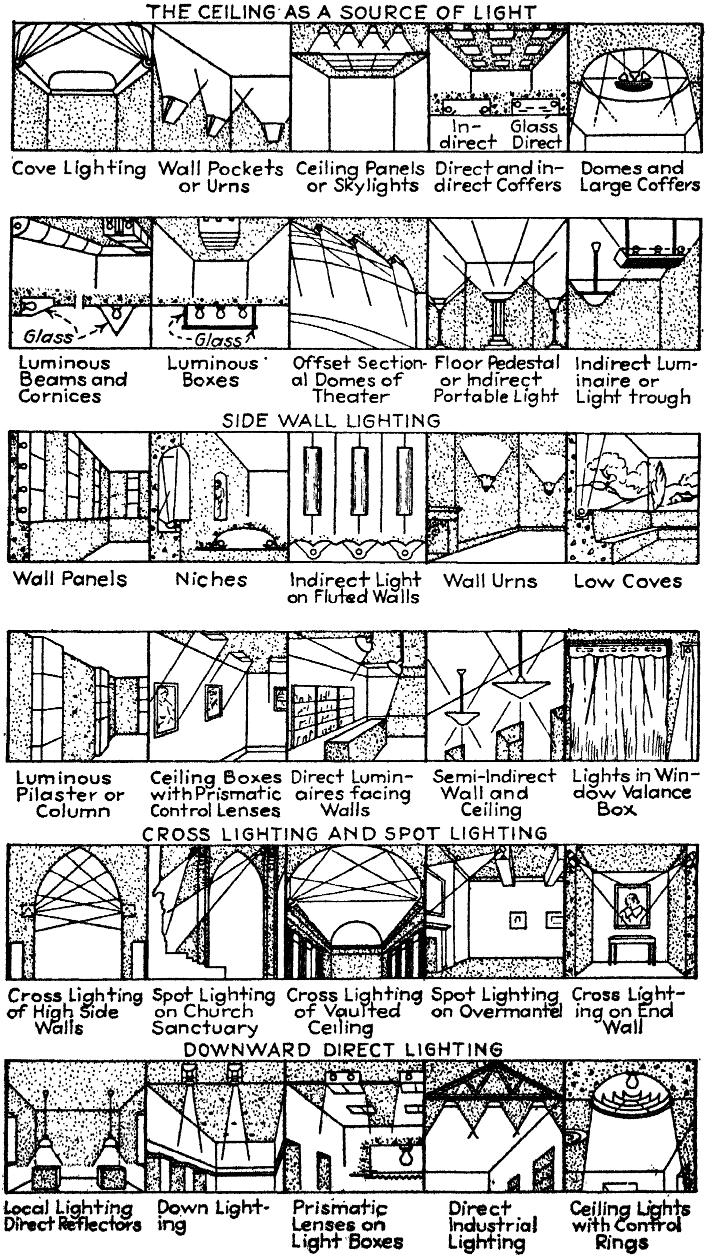

THE CEILING AS A SOURCE OF LIGHT
In-direct
Glass Direct
Cove Lighting
Wall Pockets or Urns
Ceiling Panels or Skylights
Direct and indirect Coffers
Domes and Large Coffers
Glass
Glass
Luminous Beams and Cornices
Luminous Boxes
Offset Sectional Domes of Theater
Floor Pedestal or Indirect Portable Light
Indirect Luminaire or Light trough
SIDE WALL LIGHTING
Wall Panels
Niches
Indirect Light on Fluted Walls
Wall Urns
Low Coves
Luminous Pilaster or Column
Ceiling Boxes with Prismatic Control Lenses
Direct Luminaires facing Walls
Semi-Indirect Wall and Ceiling
Lights in Window Valance Box
CROSS LIGHTING AND SPOT LIGHTING
Cross Lighting of High Side Walls
Spot Lighting on Church Sanctuary
Cross Lighting of Vaulted Ceiling
Spot Lighting on Overmantel
Cross Lighting on End Wall
DOWNWARD DIRECT LIGHTING
Local Lighting Direct Reflectors
Down Lighting
Prismatic Lenses on Light Boxes
Direct Industrial Lighting
Ceiling Lights with Control Rings

Fig. 10-1.—Ways of using light.

quickly collects dirt or dust and must be frequently painted to maintain its efficiency.

Reflectors or prismatic glass covers should be used where wide distribution is necessary, as in the case of a wide room or coves close to the ceiling. Concentrating specular reflectors of high efficiency placed close enough together to prevent spottiness are recommended for best results in relatively wide rooms. Prismatic lens plates and Fresnel lens sections may be used with reflectors to form a sheet of light projecting at a narrow angle across the ceiling.

Cove dimensions depend upon the type of reflector and the wattage of lamps. A 3-in. trough using tubular or lumiline lamps represents the smallest practical cove with limited light output. Allow from 5 by 5 in. for 40-watt lamps to 10 by 10 in. for 200-watt equipment. See Fig. 10-1 for relative dimensions of representative units.

Ceilings lighted by coves high up on the wall are likely to reveal any surface imperfections or irregularities, especially if painted with gloss paints. Where the coves cannot be dropped well below the ceiling line it is usually better to use a textured treatment, *e.g.*, sand finish or palm finish, and to let the light bring out the texture, than to attempt to produce a mechanically true ceiling.

Efficiency of cove lighting varies widely. Under very favorable conditions a plaster cove may have a coefficient of utilization of 18 to 20 per cent. With specular reflectors of high efficiency the coefficient would rise to 25 per cent or more. If the reflection factor of the ceiling is less than 70 per cent these values must be reduced proportionately. For the application of these data see section on Calculations for Luminous Elements.

Indirect ceiling illumination of any other type, *e.g.*, from reflectors mounted in pylons, floor stands, side-wall brackets, or suspended in direct luminaires and light troughs, should follow the principles indicated for cove lighting. The light source should be above eye level; the light should have a chance to spread before reaching the ceiling; and distribution of these sources should be such as to avoid spottiness or unequal lighting of ceiling areas. When such sources project their light vertically or nearly so, the character of the plasterwork is of little importance and even beams and other obstructions often may be tolerated.

Panel lighting for ceilings, side walls, columns, pilasters, or soffits requires space behind the glass panel face to contain the lamps and some form of diffusely reflecting surface. Important requirements are (1) a simple means of access for relamping or maintenance and (2) the glass face should be uniformly lighted or the lighting uniformly graded as desired, without revealing the position of the lamps or showing spottiness. This requires the right combination of background reflectors, lamp spacing, and choice of diffusing glass. Obviously the mechanical construction of built-in lighting units must be of sound design, holding the glass securely but with proper provision for expansion and having means of access to the lamps and interior surfaces.

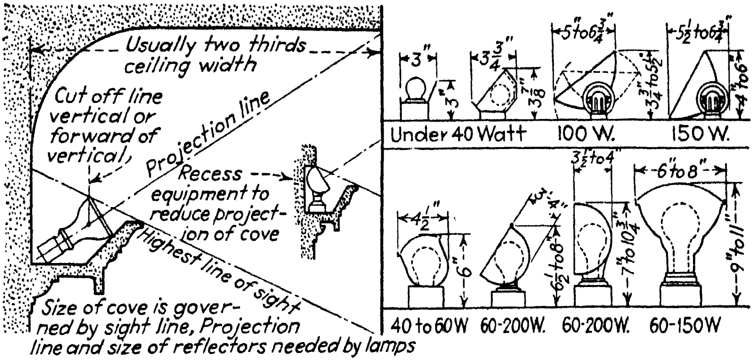
The reflecting niche may be rectangular or curved provided a good diffusing surface is employed, *e.g.*, flat white paint or mat enamel. Shapes commonly used and their performance characteristics are shown in the diagrams accompanying Table 10-1. Lamp spacings for visual uniformity depend on the cover glass used, as follows:

	Distance from glass, inches	Spacing between lamps, inches
Flashed opal glass	4	6
Flashed opal glass	6	9
Flashed opal glass	8	14
Sandblasted or acid-etched crystal glass	12	4

The wattage of the lamps makes practically no difference in the uniformity of brightness. With a high-reflection background or where a grille over-lay is used the spacing of lamps may be somewhat wider than above for the same distance from the glass. All measurements are to the centers of the lamp bulbs. For data on the transmission, reflection, and absorption factors of various translucent materials see Table 9-14.

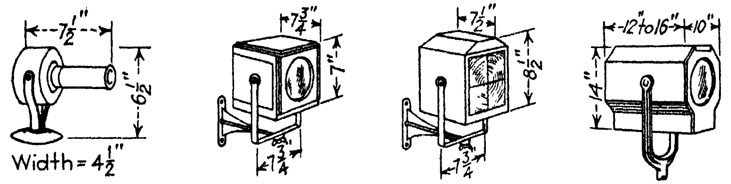
If the glass of the panel is not one piece, the dividing strips or frames should come in the darker spaces between lamps.

Sockets should be of porcelain, and wire used in light boxes should be asbestos covered or at least have slow-burning insula-

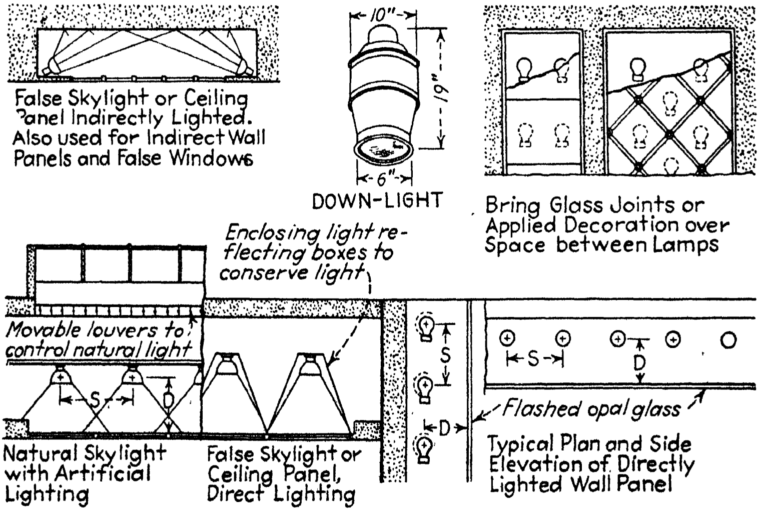

Usually two thirds ceiling width
Cut off line vertical or forward of vertical,
Projection line
Recess equipment to reduce projection of cove
Highest line of sight
Size of cove is governed by sight line, Projection line and size of reflectors needed by lamps
3"
3"
$3\frac{3}{4}$"
$3\frac{7}{8}$"
5 to $6\frac{3}{4}$"
$3\frac{3}{4}$ to $5\frac{1}{2}$"
$5\frac{1}{2}$ to $6\frac{3}{4}$"
4 to 6"
Under 40 Watt
100 W.
150 W.
$4\frac{1}{2}$"
6"
$6\frac{1}{2}$ to 8"
$3\frac{1}{2}$ to 4"
$7\frac{1}{2}$ to $10\frac{3}{4}$"
6 to 8"
9 to 11"
40 to 60W
60-200W.
60-200W.
60-150W

DESIGN OF COVE LIGHTING

TYPICAL COVE LIGHTING UNITS



TYPICAL SPOTLIGHTS


False Skylight or Ceiling Panel Indirectly Lighted. Also used for Indirect Wall Panels and False Windows
10"
19"
6"
DOWN-LIGHT
Bring Glass Joints or Applied Decoration over Space between Lamps
Enclosing light reflecting boxes to conserve light
Movable louvers to control natural light
S
D
S
D
S
D
Flashed opal glass
Natural Skylight with Artificial Lighting
False Skylight or Ceiling Panel, Direct Lighting
Typical Plan and Side Elevation of Directly Lighted Wall Panel

SKYLIGHTS AND CEILING PANELS

DIRECTLY LIGHTED WALL PANELS

FIG. 10-2.—Design details and approximate dimensions of typical built-in light sources.

tion to withstand the heat generated in the enclosed space. Each box should have some means of ventilation or should have ample radiation surface to dissipate this heat.

Frosted, carved, etched, and ground glasses are such poor diffusion mediums that they should be backed by a plate of flashed opal glass or else the lights should be placed at one or both sides of the light box, as for an indirectly lighted niçhe, and the background relied upon for uniform effect.

Luminous boxes, beam strips, and coves are governed by the same considerations in design as lighted panels. Performance characteristics are given in Table 10-1.

Lighted niches may be designed in several ways as illustrated in Fig. 10-1 and Table 10-1. In one method lamps are concealed at one or both sides of the niche behind opaque members. If on both sides, the considerations affecting the shape of cove lighted ceilings govern the form of the niche. If on one side only, the niche must be formed to distribute the reflection of the light rays within the niche so as to produce a uniform or graded effect as desired. A niche may also be lighted from below, as shown in Fig. 10-1, or from a suitable soffit light at the head.

Another method places the light source outside of the niche behind an opaque reflector or trough after the manner shown in Fig. 10-2 for side-wall lighting of fluted surfaces and in Table 10-1, unit 2. Backgrounds of niches, which are usually employed for their architectural or decorative value, may be of either diffuse or specularly reflecting material according to the effect desired.

Ceiling coffers may be lighted as niches or as panels as diagrammatically illustrated in Fig. 10-1.

Spotlights consist of projectors having lenses and light housings similar to those used in stage work. Since only the lens or an aperture is usually permitted to show on the surface, space adequate to conceal the housings must be provided in the ceilings, walls, false beams, or other places of concealment, and provision must be made for access to them for relamping and cleaning. Dimensions depend upon the capacity of the projector and the spread of light desired. In Fig. 10-2 are shown several representative units and methods of mounting them, with a range of dimensions indicated.

Shielded ceiling lights, consisting of direct lighting units projecting their light downward through shields or fixed louvers which prevent the lamp and reflector from being visible at ordinary angles of view, are usually recessed in the ceiling as relatively small circular or polygonal panels. The shields should be so designed as to intercept the minimum amount of light flux. Louvers can be arranged, if desired, in interesting symmetrical geometric forms so that they literally become a part of the decorative scheme. Similar units may be suspended after the manner of direct luminaires and reflectors. Commercially available units range from 6 to 18 in. in diameter; those set flush in ceilings usually need a space from 8 to 24 in. in depth, the lower wattage lamps, of course, taking the smaller reflectors.

Prismatic-lensed soffit lights are commercially available in units of one, two, or more light boxes with control lenses 6½, 8½ or 12 in. square. The depth of boxes varies from 4½ to 13 in., depending on the wattage. They are usually recessed in the ceiling or some beam or other horizontal projection. Their lamps are usually adjustable for control of distribution as shown in Fig. 10-1.

Various ways of using light for seeing (as distinguished from purely decorative applications) are diagrammatically presented in Fig. 10-1 as well as in many of the accompanying illustrations. The characteristics and limitations of the principal methods may be summarized as follows:

Ceiling reflection, in which light sources are directed upon a white or light colored ceiling and thence redirected and diffused throughout the room, produces a soft general lighting of excellent quality. It is generally most effective when side walls are also of rather light tone; otherwise the ceiling may appear excessively bright and thus distract the eye by its contrast with dark walls. It is also very useful as a source of moderate-level general lighting, in the order of 3 to 6 foot-candles, when supplemented by local lighting of special areas or work surfaces at higher intensities. Ceilings may thus be lighted by coves, indirect luminaires of trough or bowl shape suspended from the ceiling, pylons, or floor stands with concealed reflectors above the eye level, and wall pockets, brackets, or strips like short sections of coves mounted on side walls or columns. With indirect lighting the luminaires themselves may be opaque or slightly luminous by transmitted light. In Fig. 10-1 are shown representative methods of using the ceiling as a light source.

Direct ceiling sources, including ceiling beams, illuminated coffers and domes, luminous false beams and cornice moldings, and luminous glass boxes, differ from indirect ceiling reflection in that they introduce areas of relatively great brightness in contrast with the remainder of the ceiling and hence have considerable attention value. They usually have somewhat the same effect of attracting the eye upwards as an indirectly lighted ceiling that contrasts sharply with dark walls. Where this degree of prominence of the light source is desired or acceptable and where the units are arranged in a pleasing and logical pattern that gives good coverage of the room, they may provide general lighting of moderate to fairly high levels. The disposition of visible light sources on the ceiling or suspended therefrom is usually superior to side-wall lighting for the reason that it is less distressing to have them well above the eye level than in direct line of vision.

One form of direct ceiling lighting places the lamps themselves in boxes or reflectors above the ceiling level and sends controlled beams down through relatively small openings which do not greatly distract the eye. One form, the downlight, employs an elliptical reflector equipped with lenses concealed above the ceiling level with only small apertures 4 in. or less in diameter appearing on the ceiling surface. Another type employs an open reflector having louvers or shields that cut off direct view of the lamp from all normal angles of vision, and a third uses reflectors and prismatic refracting plates or control lenses. The light is projected downward in all cases. As a class these sources are particularly useful where the ceiling itself is unimportant to the lighting composition and where the floor level must be well lighted. Such schemes give better light control than any other commonly used method.

Indirect side-wall lighting, if developed uniformly over large areas and at moderate-brightness levels, has substantially the same value as indirect ceiling illumination but with the important exception that it tends to form silhouettes of persons or objects viewed toward the wall. Indirect side-wall light sources are shown in Fig. 10-1. They include low coves concealed behind built-in furniture; coves incorporated in window head valance boxes or above bookcases, show cases, and similar built-in units; indirect lighting produced by projecting opaque light troughs that reflect against the adjacent side wall; and soffit lights in ceilings or beams which, by means of prismatic reflectors, direct most of their light flux on the adjacent side wall.

Direct side-wall lighting, using such sources as luminous wall panels, niches, wall urns, and side-wall brackets of any type, has high attention value because these sources are in the direct line of vision. Recessed sources tend to produce sharp contrast between the lighted sections and the indirectly illuminated areas which surround them. Side-wall lighting is valuable for decorative and architectural purposes and for good illumination of vertical surfaces, such as manikins and dress models in shops and stores, but they do not provide uniform distribution of their light flux on the horizontal plane of the room.

Crosslighting may be used on walls or on vaulted ceilings, as illustrated in Fig. 10-1. As the name implies, projectors (usually concealed or recessed and shielded from the eye level) cast their light across the room from both sides or from two different angles toward the same area. This method is particularly useful when side walls well above the eye level carry murals, mosaics, or other important decorations requiring good illumination from invisible sources. It also serves as a means of correcting spottiness caused by cove lights, wall brackets, etc., by crosslighting the shadowed areas.

Spotlighting is one-way lighting, usually employing projectors with lenses but sometimes with reflectors only, used to give special illumination of a limited area as in theater practice. A mural, statue, oil painting, or other axial feature may thus be made to dominate the lighting composition. The spotlights must be so located as to be out of the direct line of vision and to produce no troublesome reflections or glare. Possible locations may usually be found within chandeliers of special design, in ceiling beams or coffers, or in columns or wall brackets (see Fig. 10-1).

Ceiling and side-wall fixtures and luminaires are by no means made obsolete by modern lighting standards, though their selection and use are now a matter of intelligent consideration rather than mere habit or precedent. The greatest value of luminaires is their flexibility and economy in securing uniform distribution of light over large areas with the minimum of outlets and lamps.

The modern fixture, however, is not merely an adaptation of an old candle, oil, or gas device with incandescent lamps at the ends of metal arms but, rather, incorporates in its construction reflectors, refractors, and other devices for controlling the distribution of light and limiting visible brightness. It may follow traditional lines and may even have electric candles exposed, but the ingenious designer conceals in the body or structure the light sources which really furnish the illumination.

Portable fixtures, including table and floor lamps, belong strictly in the local lighting classification and are invaluable for stepping up lighting intensities at work centers such as desks and tables and at reading chairs. Suspended direct lighting opaque reflectors hung low enough so that the reflectors cut off all view of the lamp, have the same function in commercial and industrial applications over machines and work surfaces.

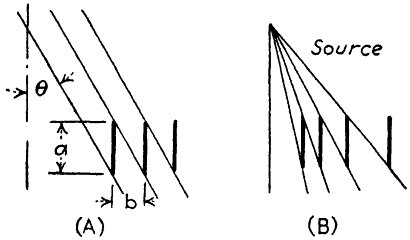


FIG. 10-3.—Louver design: (*A*) For general lighting, (*B*) For spill-light control.

Reliance upon portable lamps for general illumination is rarely good practice though currently popular in residence work. Such use of relatively high intensity areas scattered throughout the room completely distorts the daytime composition, often attracting attention to areas of minor importance and neglecting others that should normally dominate. They leave dark shadows beneath furnishings and cause excessive eyestrain due to the sharp contrasts of light and deep shade.

Built-in Direct Lighting.—Direct lighting without hanging ceiling fixtures is gaining much favor and recognition through the use of louvers and control lenses to intercept those light rays which would otherwise reach the eye and produce annoyance, glare, or decrease in effectiveness of the system.

A *louver*, as applied to lighting equipment, consists of a series of fins arranged to shield the filament of the lamp from view in one or more directions or to cut off the light in directions where it might be objectionable. The principle of the use of louvers is shown in Fig. 10-3,[1] while various patterns are shown in Fig. 10-4.[1] With an efficient concentrating-type reflector the louver losses are comparatively low in a well-designed louver system for the reason that the louvers being open, offer no direct obstruction to the projected light. With wider angle reflectors and where diffusing plates may be introduced above the louver the losses are greater.

The first extensive use of louvers in lighting was in show-window installations, parallel fins being used. A more recent type is the U- or horseshoe-type louver shown as No. 9 in Fig. 10-4. This unit shields in all necessary directions, except for island windows, and much of the light flux is not intercepted.

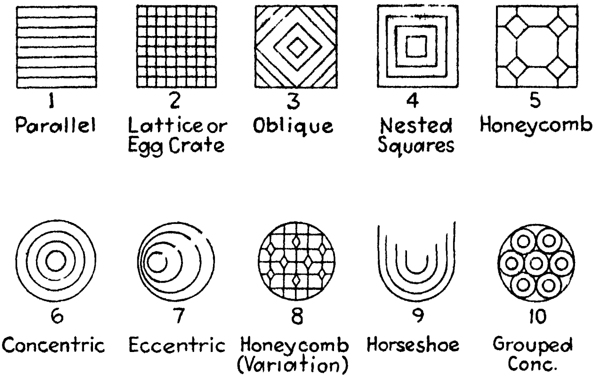


Fig. 10-4.—Louver patterns.

Concentric circular louvers are used effectively recessed into ceilings of large interiors as stores, dance halls, dining rooms, etc., sometimes in conjunction with color filters.

Control lenses furnish a means of delivering special distributions of glareless high intensities directly and economically. They are prismatic, crystal glass plates made in various sizes and shapes and possess the optical characteristics of lenses. They control the distribution of light from the unit of which they are a part by being placed across the aperture and directing the light into the desired pattern.

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[1] J. L. Stair and L. H. Graves, *Trans. Illum. Eng. Soc.*, vol. 31, p. 249, 1936.

A study of Fig. 10-5 will indicate how the control lenses function. With the lamp filament in position *A* the light flux produces a focusing light similar to curve 1. When the filament is in position *C* the light is spread producing an intensive distribution like curve 3. The placing of the lamp to the right in the positions *D*, *E*, and *F* produces distributions 4, 5, and 6, while positions *G*, *H* and *I* produce curves 7, 8 and 9. Other lenses give different distributions of light.

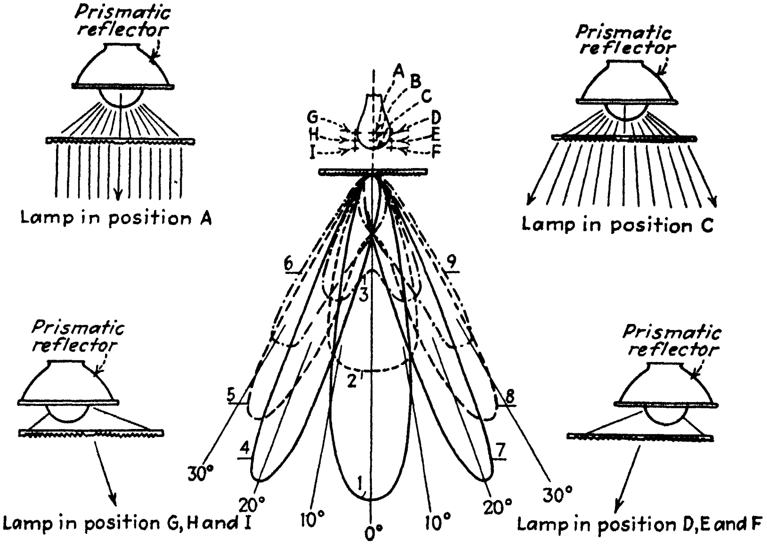

FIG. 10-5.—Composite polar-coordinate curve showing light distributions from a Holophane controlens with the lamp in nine different focal positions.

Prismatic reflectors designed for and back of the control lenses insure best results.

Klieglights are spot floodlights. Essentially they constitute a reflector and lens system for collecting and projecting the light rays from a biplane filament lamp, coordinated with a system of adjustable shutters for instantaneously regulating the size and shape of the light beam in any desirable manner. These are assembled in a suitable housing which may be mounted on either a portable floor stand or an appropriate fixture for permanent installation.

They produce a brilliant, clear, uniform light, covering any required area, projecting any desired pattern of illumination, and furnishing white or colored light as desired. The efficiency is high and the simplicity, range, and accuracy of light control are excellent. An illustration of the use of one type of these lamps is shown in Fig. 10-6.

Architectural designed lighting has been and is taking new forms, *e.g.*, pylons, columns, pilasters, panels, spandrels, beams, coves, coffers, moldings, niches, and decorative patterns, carrying over into related wall, ceiling, and portable luminaires [1]

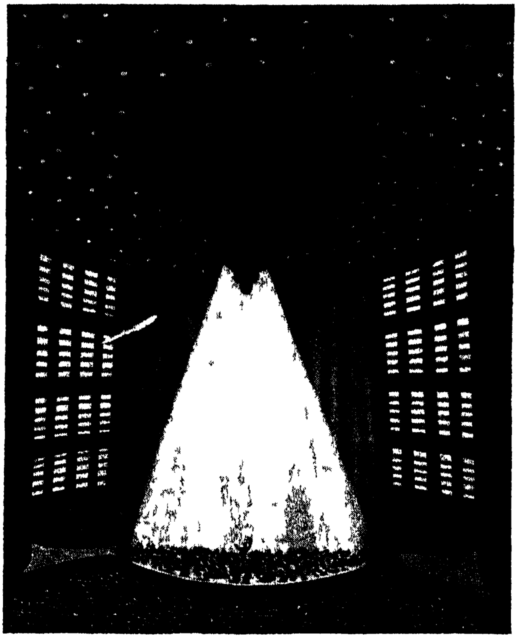

FIG. 10-6.—Center Theatre, Radio City, New York. Front lighting from chandelier

Structurally they consist of recesses either open or with light-transmitting covers, of translucent projecting elements, or of self-contained detached units.

Extended luminous recesses, coves, grooves, and coffers are well adapted for providing the main illumination of a room. Sometimes the recess may be illuminated most suitably from the edges. Again the light sources may be carried in narrow opaque sections projecting from the recess.

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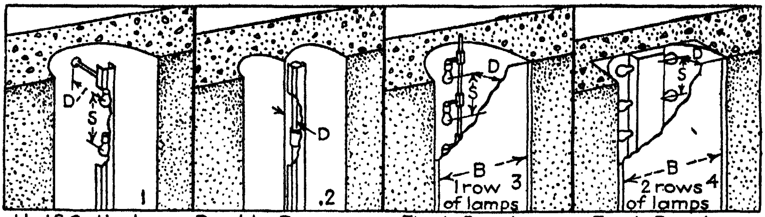
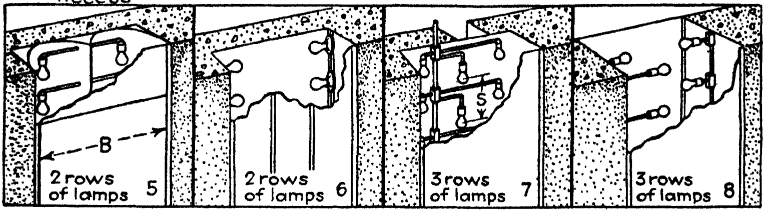
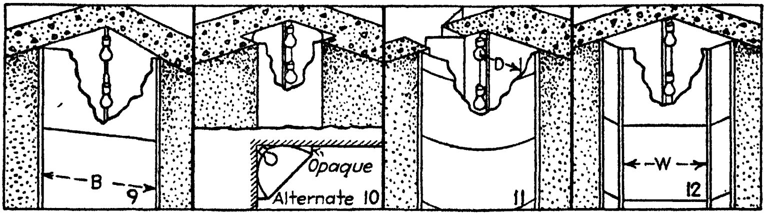
[1] POTTER and MEAKER, *ibid.*, vol. 26, p. 1025, 1931.



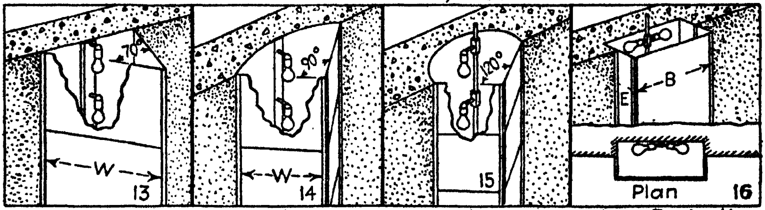
Half Cylinder Recess Double Recess Flush Panel Flush Panel



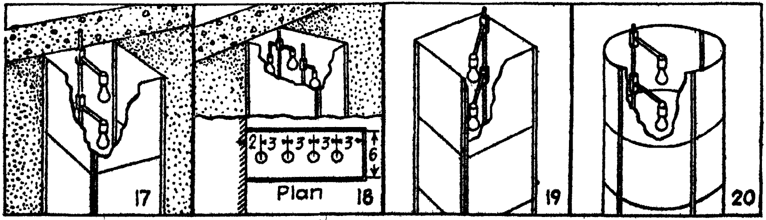
Flush Panel Flush Panel Flush Panel Double Window



Corner Panel Corner Panel with Reflector Quarter Cylinder Projecting Element



Projecting Element 70° Projecting Element 90° Projecting Element 120° Shallow Projecting Element



Square Projection Deep Projection Square Column Cylinder

FIG. 10-7.—Luminous architectural elements.

Luminous panels substantially flush with wall or ceiling may be adapted to many conditions and lend themselves to many forms of decoration. They may carry a deeply etched or molded pattern, a design may be fired on in ceramic color, or they may serve to give emphasis to a grille or graceful tracery.

The appearance, character, and efficiency are determined by the glassware or translucent medium forming the surface of the panel. The choice of material for the panel face, its color, and decoration are determined by the necessity for harmony with the rest of the structure by day as well as the desired luminous effect after dark.

Attached and projecting elements are almost as readily applied to old interiors as to new structures. They may range in form from luminous beams or moldings to the modern type of close-to-ceiling luminaires.

Uniformly bright luminous elements have either a covering of highly diffusing translucent material or an exposed, uniformly illuminated diffusing background. Examples of designs of these luminous elements together with data as to efficiency and brightness of full size models are shown in Fig. 10-7[1] and Table 10-1.

The data apply to mat white reflecting surfaces of 75 per cent reflection factor with wiring devices painted same as background. The framing is 0.5 in. wide. The flashed opal has a transmission factor of 50 per cent; solid opal 1, 32 per cent; composition 0.01 in. thick, 23 per cent; solid opal 2, 18 per cent. The lamp axes were parallel to the glass.

These several elements may be applied in many ways on ceilings, walls, corners, cornices, etc. The performance of other forms may be estimated by comparison with those shown in Table 10-1.

The lumiline lamp is ideal for this class of lighting and is replacing other types of incandescent lamps. It is obvious that the uniformity of brightness will be greatly improved.

The distribution curve for a typical panel unit is shown in Fig. 10-8. These values are, of course, in a plane at right angles to the longest dimension of the unit and are for the open-unit, diamond glass and for flashed opal glass, respectively.[2]

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[1] *Ibid.*

[2] *Ibid.* vol. 31, p. 1007, 1931.

TABLE 10-1.—EFFICIENCY OF LUMINOUS ARCHITECTURAL ELEMENTS*

Unit No.	Width tested, inches	Spacing of lamps	Distance from lamps to glass	Efficiency, (percentage of lamp lumens)					Notes†
				Open	Flashed opal	Solid opal No. 1	Composition	Solid opal No. 2	
1	25	$1.9D$	......	43					For surface of 0.75 reflection factor; for other surfaces, 0.52 × reflection factor
2	25	1¾ in.	......	39					For surface of 0.75 reflection factor; for other surfaces, 0.57 × reflection factor
3	12	$1.5D$	$0.67B$	..	49	34	27	18	For rectangular back use 0.95 of efficiency values given
4	24	$1.5D$	$0.33B$	..	51	37	29	22	Row spacing is ½ of panel width
5	24	$1.2D$	$0.27B$	..	49	34	27	20	This form of reflector, with lamp rows spaced ⅔ of panel width, produces desired transverse uniformity with shallow cavity
6	24	$1.2D$	$0.27B$	..	49 (including ground-glass panel)				Lamps centered on flashed opal panels. Some spottiness when viewed at angle
7	24	$1.25D$	$0.27B$	..	49	34	27	20	
8	24	D	$0.33B$	..	65	48	38	29	Efficiency of two faces
9	20	$1.5D$	$0.4B$	..	54	38	30	23	Spacing ratio applies for longitudinal uniformity. Brightness fades off from center to sides
10	10½	$1.5D$	$0.67B$	..	41	29	23	17	Transverse uniformity is attained in the narrow panel
11		$1.5D$	9 in.	..	57	41	31	25	For half cylinder see data of Unit No. 13
12	$W = 16$	$1.5D$	$0.67W$	..	54	38	30	23	
13	$W = 13$	$1.5D$	......	..	76	57	43	39	For half cylinder use 1.05 times given efficiency
14	$W = 14$	$1.5D$	$0.5W$	..	65	46	36	32	The lamps should be equidistant from and centered behind the sides
15	$W = 11½$	$1.5D$	$0.67W$	..	57	41	31	28	The lamps should be equidistant from and centered behind the sides
16	24	$1.4D$	$0.37B$	..	63	46	36	27	Projection $E = 0.25B$. Lamps located behind plane of wall about ½E
17	12	$1.5D$	......	..	74	56	44	40	
18	12	$1.1D$	(3 rows)	..	65	48	38	29	
19	12	$1.4D$	......	..	83	67	53	45	Framing to conceal wiring
20	Diam. 12	$1.4D$	......	..	87	71	58	50	Conduit riser located on least conspicuous side

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* *Amer. Architect*, December, 1934.

† Construction of Test Units. Reflector or cavity surfaces of 75 per cent reflection factor, mat white; wiring devices painted same as background. Framing ½ in. wide; lamp axes parallel to plane of glass; transmission factors of glasses used; flashed opal glass, 50 per cent; solid opal glass No. 1, 32 per cent; composition (0.01 in. thick), 23 per cent; solid opal glass No. 2, 18 per cent.

Luminous lighting systems, whether for illumination or decoration, must be constructed and arranged with due attention to architectural harmony and appearance. At the same time they should be so placed and spaced that illumination in sufficient amount and of a uniformity appropriate to the visual requirements of the area lighted is supplied wherever needed.

In a decorative unit the brightness may extend to very low values. This is not feasible when units must also supply the illumination for a room. However, the brightness must not exceed certain maximum values. The limits for comfort and unimpaired vision depend on a number of varying conditions.

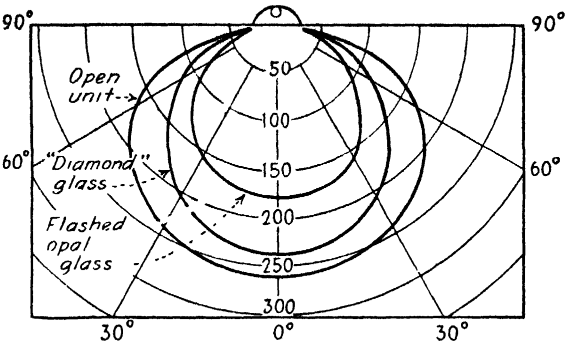

FIG. 10-8.—Candlepower-distribution curves of a simple panel unit using six 25-watt spot-type light sources on 5-in. centers.

With light surroundings the units may be brighter than when the background is dark. As the illumination in a room is increased, glare from constant brightness is lessened. If the elements are attached to a high ceiling or placed well to the side of the general direction of view the brightness may be materially higher than for elements on a low ceiling or on a front wall. Similarly a flush panel in a ceiling may be brighter than a beam unit since the direction of maximum brightness is downward in the former.

As the area of the source is increased the brightness is decreased for the same amount of light. However, glare is also produced by excessive amounts of light directed toward the eye.

The position of the luminous source governs the permissible brightness. These may be approximately as indicated in Table 10-2.

TABLE 10-2.—PERMISSIBLE BRIGHTNESS RELATIVE TO LUMINOUS SOURCE*

	Foot-lamberts
Projecting ceiling elements 20 ft. or more above floor.	500
Projecting elements on low ceilings, particularly in large rooms	250
Projecting elements on low ceilings, for mezzanines	175–225
Wall panels or recesses in passageways	200
Wall panels and niches in places of business, where not directly in line of sight	125
Decorative panels constantly in field of view	75

* *Am. Architect*, December, 1934.

It will be seen that these values are all well below the 750 to 1,500 ft.-lambert range usually found acceptable for the conventional types of luminaires of restricted area used in direct lighting.

In general, where these luminous sources are used to produce the illumination throughout a room they should be ceiling units. Side-wall panels, unless high on the walls, while giving fairly high levels of illumination on adjacent horizontal surfaces, do not effectively light more remote areas. Vertical surfaces are, however, well lighted by wall panels and they are useful for producing the side light in rooms where the light in general is projected downward from high ceilings.

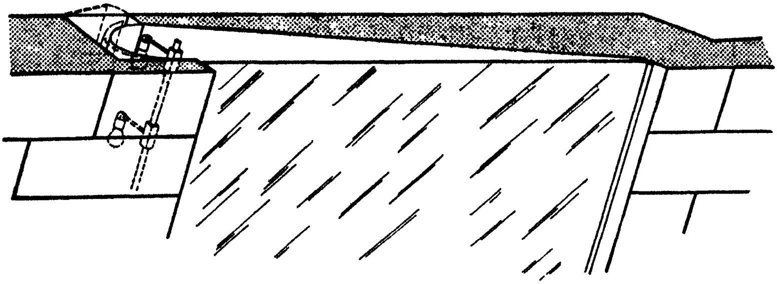

FIG. 10-9.—A type of cavity construction for producing a transverse gradation of brightness.

Luminous Elements for Nonuniform Brightness.—The variety and character of effects to be attained by nonuniform luminous elements are bringing them into increasing prominence. Gradation or shading of brightness across the panel has interesting applications especially when the panel carries grilles or decorative designs.

An example of this type of construction is shown in Fig. 10-9. The semi-diffusing, opalescent, figured, and depolished glasses are particularly adapted to this type of element. The advantages of the partially diffusing glasses are their relatively high transmission and their greater life and sparkle, particularly pronounced in the configurated glasses. Tubular lamps will produce best results as to longitudinal uniformity.

The graded-brightness panel should be considered when structural limitations have room for only a shallow cavity. When corrected for the difference in transmission in the glasses used the relative values of efficiency and brightness factor, as given in Table 10-1, will apply approximately.

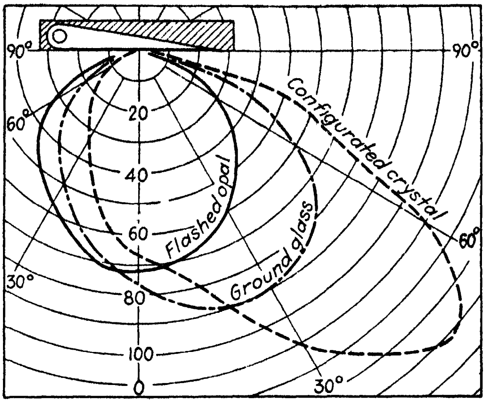

FIG. 10-10.—Light distribution from a luminous element covered with flash opal, ground, and configurated crystal glasses.

The variation of candle power with angle of view for flash opal, ground, and configurated crystal glasses used in the panel shown in Fig. 10-9 is shown in Fig. 10-10.

Reflecting materials for luminous reflecting elements are chosen from an architectural standpoint by structural fitness, texture, color, and permanence; from a lighting standpoint by light-reflecting efficiency and the light distribution characteristics of the finish, considered together with the form and position of the element and probable angles of view. They consist of the common building materials and paints, glazed and enameled materials, and polished metals. Some of the properties of reflecting materials are indicated in Fig. 10-11.[1]

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[1] WARD HARRISON and C. E. WEITZ, Illumination Design Data, LD-6A, Nela Park Eng. Dept., General Electric Company, 1936.

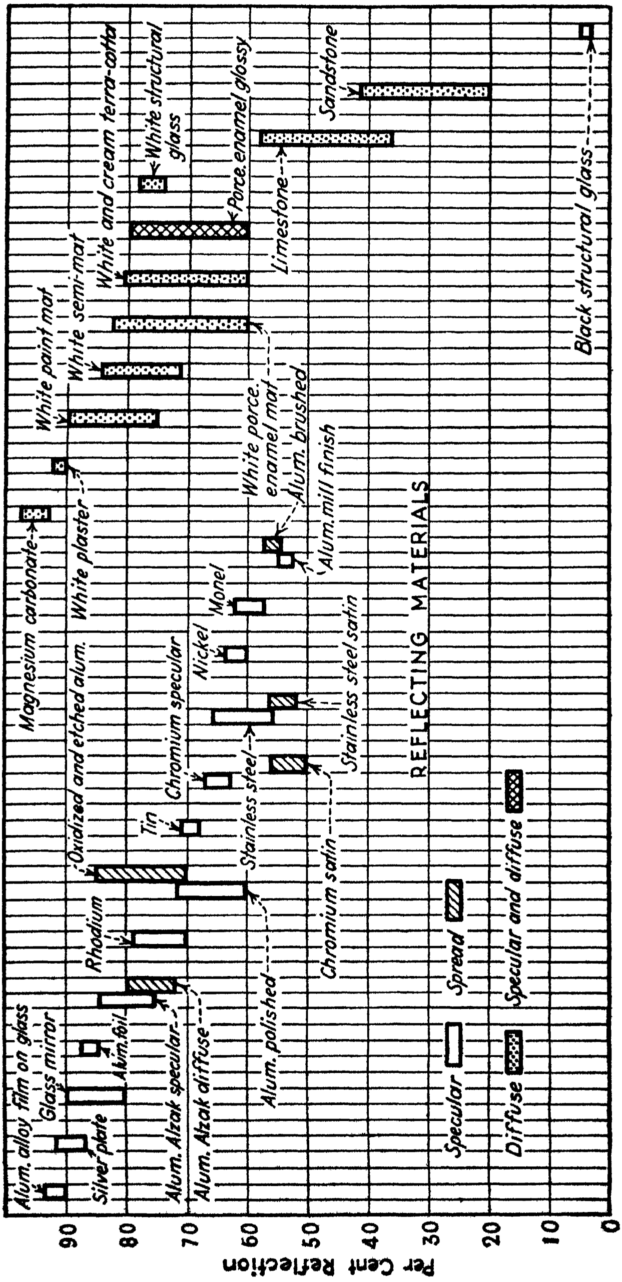

FIG. 10-11.—Characteristics of reflecting materials.

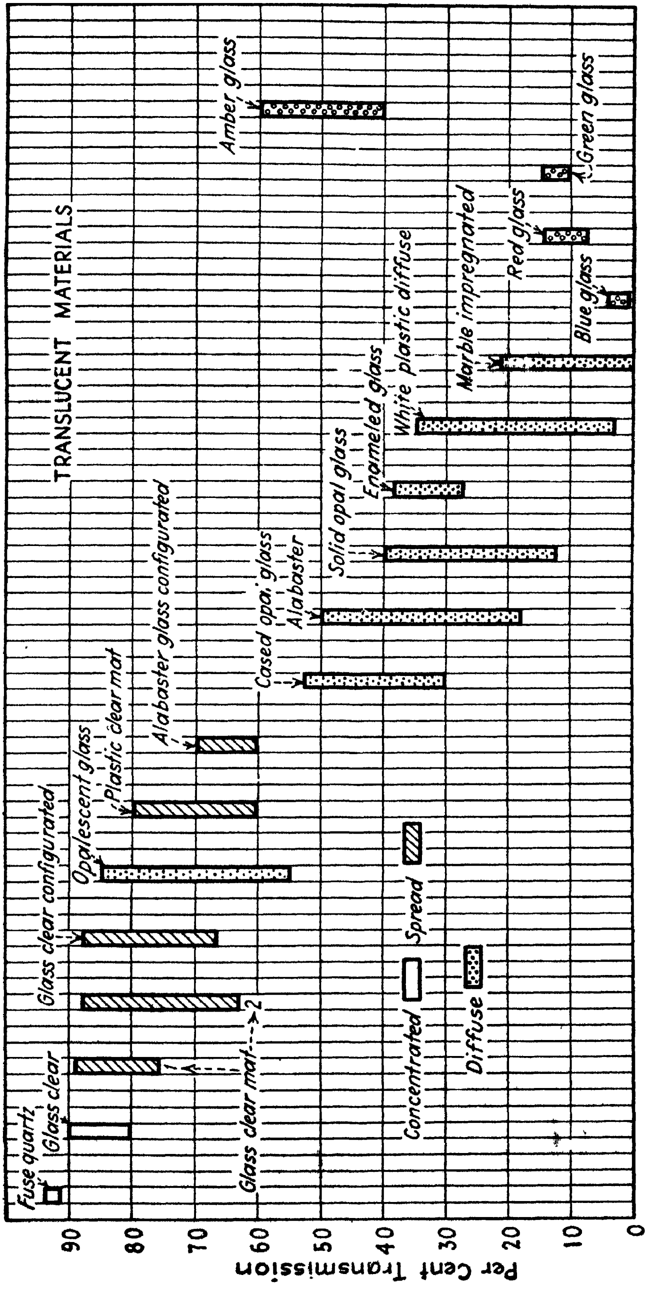

FIG. 10-12.—Characteristics of translucent materials.

Translucent materials run the complete range of transmission efficiency from about 95 per cent for clear glass down to but a few per cent for colored marbles, with an equally wide range in light-diffusing characteristics. As in the case of reflecting materials the choice of transmitting materials is governed (1) by color, texture, and appearance, lighted and unlighted; (2) by efficiency, diffusing properties, and maintenance. For luminous areas with apparently uniform brightness at all angles of view highly diffusing materials are necessary, except where the incident light itself is highly diffused.

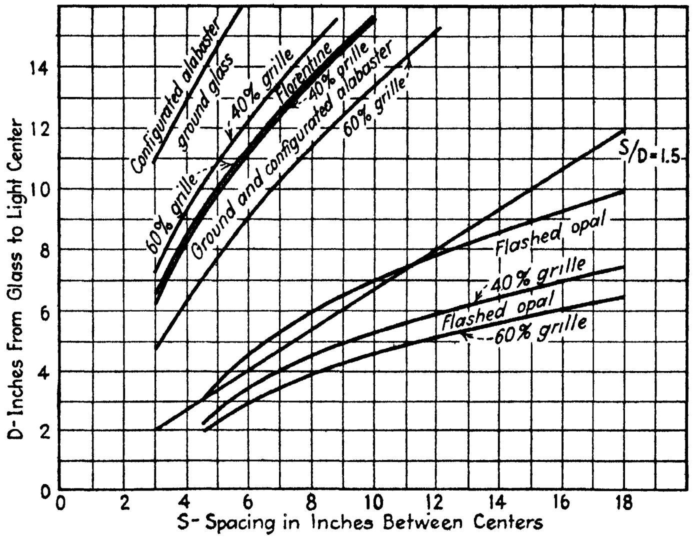

FIG. 10-13.—Lamp spacing for acceptable uniformity of brightness. With grilles or decoration on the glass lesser uniformity is permissible.

The choice of translucent materials is influenced also by their appearance outdoors in daytime or when unlighted indoors. Here the amount of light reflected is of special importance. The higher the reflection factor the whiter the surface will appear in daylight, assuming largely diffusing characteristics. For example, if a definitely white surface is desired a homogeneous opal glass should be used. The cased opals, opalescents, mat surface and configurated glasses assume progressively grayer tones. Texture and color may be a consideration. In Fig. 10-12[1] are indicated some of the properties of translucent materials.

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[1] WARD HARRISON and C. E. WEITZ, Illumination Design Data, LD-6A, Nela Park Eng. Dept., General Electric Company, 1936.

Where lamps are placed behind diffusing glass the maximum permissible spacing between lamps follows the common rule for general lighting, *i.e.*, a spacing of $1\frac{1}{2}$ times the distance of the filament back of the glass. Variations from this rule for glasses of various diffusing properties and for various sizes of panel are shown by the curves in Fig. 10-13.[1] Where lamps are placed in silhouette troughs or miniature coves at the sides of the luminous area, the spacing of lamps concealed within the trough as well as the distance between troughs is subject to the same general rule, though variations are permissible in particular cases.

Calculations for Luminous Elements.—When the designer has decided upon the type of element to use the procedure is similar to the flux-of-light method of Chap. IX.

$$\text{Total required lumens output of system } F = \frac{\text{foot-candles } E_0 \times \text{area of room, } S\text{, square foot}}{\text{utilization factor } C}$$

$$\text{Luminous area required in elements } S_e\text{, square foot} = \frac{\text{total required lumen output } F}{\text{limiting brightness selected, } B\text{, foot-lamberts}}$$

$$\text{Lamp lumens } N = \frac{\text{lumens required } F}{\text{efficiency of elements} \times \text{depreciation factor } M}$$

The foot-candle intensities recommended for different services may be found in Table 9-4. The lumens per lamp are given in Table 9-3. The limiting brightness values in Table 10-2. The efficiencies for different elements and glassware in Table 10-1.

The values of the coefficient of utilization for uniformly bright ceiling elements are given in Table 10-3. Only two classifications are made: flush panels and projecting elements. It is obvious, however, that since the relative downward and sidewise projected areas of the latter classification vary so much with the different shapes, the values for projecting elements will be both greater and less than the listed values. A deep narrow beam-type element will have a smaller coefficient of utilization than a flat wide one. Panels placed at 45 deg. at the intersection of wall and ceiling are approximately as efficient as the average projecting element.

The depreciation factor will vary in different buildings and according to the form of the element, the excellence of their construction, and whether or not they are ventilated. The depreciation will probably be comparable with that of the usual types of luminaires under similar conditions.

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[1] Ward Harrison and C. E. Weitz, Illumination Design Data, LD-6A, Nela Park Eng. Dept., General Electric Company, 1936.

TABLE 10-3.—COEFFICIENTS OF UTILIZATION FOR CEILING ELEMENTS*

Percentage of light emitted by complete element reaching usual level of work surface. Multiply by efficiency of element to obtain over-all utilization.

Ceiling	Very light, 70%			Fairly light, 50%			Fairly dark, 30%	
Walls	Fairly light, 50%	Fairly dark, 30%	Very dark, 10%	Fairly light, 50%	Fairly dark, 30%	Very dark, 10%	Fairly dark, 30%	Very dark, 10%
Room index	Coefficients of utilization							
Recesses and flush-type panels								
J	0.47	0.40	0.35	0.46	0.40	0.35	0 39	0.35
I	0.58	0.52	0.48	0.57	0.51	0.47	0.51	0.47
H	0.63	0.58	0.54	0.62	0.58	0.54	0.57	0.54
G	0.67	0.62	0.58	0.66	0.62	0.58	0.60	0.58
F	0.72	0.67	0.63	0.70	0.66	0.63	0.65	0.63
E	0.78	0.74	0.70	0.77	0.73	0.70	0.72	0.70
D	0.84	0.80	0.76	0.82	0.79	0.76	0.78	0.76
C	0.86	0.83	0.79	0.84	0.81	0.79	0.80	0.78
B	0.90	0.87	0.84	0.88	0.85	0.83	0.84	0.82
A	0.92	0.89	0.86	0.90	0.87	0.85	0.86	0.84
Average of projecting types†								
J	0.33	0.26	0.22	0.31	0.26	0.22	0.23	0.21
I	0.39	0.33	0.29	0.38	0.33	0.28	0.30	0.27
H	0.44	0.38	0.34	0.42	0.38	0.33	0.35	0.31
G	0.49	0.43	0.38	0.47	0.42	0.38	0.39	0.35
F	0.54	0.47	0.42	0.51	0.46	0.42	0.43	0.39
E	0.59	0.52	0.47	0.56	0.51	0.47	0.48	0.44
D	0.64	0.57	0.52	0.60	0.55	0.51	0.53	0.50
C	0.68	0.62	0.56	0.63	0.57	0.53	0.56	0.52
B	0.73	0.66	0.61	0.68	0.64	0.95	0.60	0.56
A	0.76	0.70	0.66	0.72	0.66	0.61	0.63	0.60

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* POTTER and MEAKER, *Trans. Illum. Eng. Soc.*, vol. 26, p. 1025, 1931.

† Specifically, element with two sides at 90 deg. to each other.

To find the brightness of a luminous source in foot-lamberts compute the area of the luminous panel, niche, or projecting light box, as the case may be, in square feet and ascertain the number and size of lamps to be used therein. From data on the lamps used compute the total lumens emitted within the unit. Then from Table 10-1 and the accompanying diagrams find the type of luminous element most closely corresponding to the unit under consideration and take the efficiency in per cent for the appropriate translucent material. Multiply the total lumens emitted within the unit by the efficiency to get the approximate light output of the unit in lumens Then this net output in lumens divided by the square feet of luminous surface will give the average brightness in foot-lamberts.

To determine the size of lamps, after having selected the type of luminous element and decided on the desirable brightness, proceed as follows: Assume a projecting element as that shown by No. 14 in Fig. 10-7, having two sides each 14 in. wide and making an angle of 90 deg. with each other. Assume also solid opal glass No. 2 and a brightness of 250 foot-lamberts.

From the data in Table 10-1

$$D = 0.5W \qquad \text{and} \qquad S = 1.5D$$

Therefore

$$S = 1.5 \times 0.5 \times 14 = 10.5 \text{ in., the distance between lamps.}$$

The total area of glass per lamp is

$$2 \times 14 \times 10.5 = 294 \text{ sq. in.} = 2.04 \text{ sq. ft.}$$

$$2.04 \text{ (sq. ft.)} \times 250 \text{ (foot-lamberts)} = 510 \text{ lumens emitted per lamp by the unit.}$$

The efficiency of this unit with No. 2 solid opal glass is 32 per cent, therefore

$$510 \div 0.32 = 1{,}600 \text{ lumens per lamp.}$$

A 100-watt lamp produces 1,510 lumens and is the nearest in size.

Color.—Color adds much to luminous elements. It offers great possibilities in creating distinctive interiors, particularly of theaters and other public places. It should also play an important part in the development of nighttime designs for structures on business streets.

The color may be characteristic of the lamps or it may be in auxiliary hoods or reflector covers, on reflecting surfaces or in the glass of the element itself. If in the latter case, the element will appear in color by day. Auxiliary colored equipment offers flexibility in changing the color from time to time or in providing mobile control.

Saturated colors are only occasionally desirable except in units of restricted size. Tints are more suitable for extended elements. Mobile color effects are pleasing but the cycle of change should not be too rapid and the colors should be appropriate. A few fixed alternative color effects will, in general, prove satisfactory. Light from street lamps and show windows dilutes the color if the glass panels are white but adds to the brightness of the color if the panels themselves are colored.

For equal effectiveness many colors and tints may have much lower brightness than white lighted surfaces. The following relative values of lamp wattage give equally attractive and effective panels: white, 1; amber, 1; green, 1.5; red, 2; and blue, 4. While the typical transmission in percentages for colored hoods and roundels are: amber, 40 to 60; green, 10 to 15; red, 7 to 14; blue, 1 to 4.

A novel installation and an example of color blending is that of the Grand foyer of cinema "Le Marignan."[1] The system is totally indirect. Colored light from gaseous tubular sources is directed towards circular sections of a white ceiling. The central area is brilliantly red from neon tubes of red glass. The red is more intense due to the red glass which absorbs the orange rays. Next is a ring of deep blue from mercury tubes in blue glass. The blue glass absorbs the green and yellow lines of the mercury spectrum. The outer ceiling, also a circular ring, is white in appearance due to light from a combination of neon and fluorescent mercury tubing. The resultant illumination is a pleasing color effect. The walls and columns are terra cotta finish and the floor has a composition surface patterned in rose, buff, orange, and black.

Luminous Elements for Exteriors.—These luminous designs may also be used for exterior lighting. After the luminous pat-

[1] *Elec. World*, vol. 106, p. 644, 1936.

tern which a building is to present at night is determined, the question of brightness enters the problem. The installation is primarily for decorative or spectacular effects rather than for the illumination of adjacent areas. The values given in Table 10-4 are suggested for the usual conditions. The selection of brightness levels is influenced by the following conditions:

1. Character, size, and brilliance of immediately adjacent (competitive) displays.
2. Signs as such should always be brighter than other portions of a design.
3. Character of the institution. A conservative business will require less bright displays than a theater, for example.
4. Relations in brightness of an element to another of the same display, for the purpose of producing emphasis or a design in brightness.
5. Extent of entire pattern and size of the elements. Lower brightness may suffice when scale is large.
6. In color, a lower brightness often proves effective.

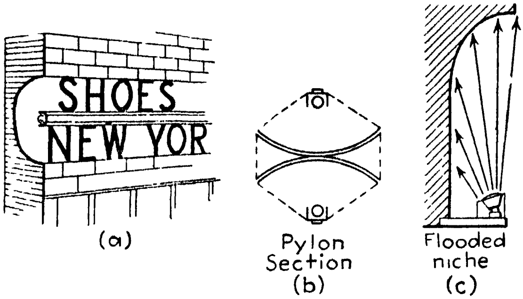
TABLE 10-4.—BRIGHTNESS LEVELS FOR LUMINOUS ELEMENTS

Type and application	General brightness of district, foot-lamberts		
	Low	Medium	High
Decorative flush elements (principal units in design), including panels and recesses	30 to 100	50 to 150	100 to 300
Decorative projecting elements (principal units in design)	50 to 130	70 to 170	150 to 300
Decorative elements, *e.g.*, spandrels and niches (particularly when subordinate elements in design)	30 to 60	40 to 80	50 to 150
Luminous background signs	90 to 150	120 to 200	150 to 350
Luminous letter stroke signs	150 to 200	200 to 400	300 to 600
Small luminous façades (*e.g.*, small entirely luminous store fronts and buildings)	80 to 120	100 to 150	120 to 200
Marquee and entrance soffits and marquee fascias	80 to 150	100 to 250	200 to 400
Luminous beams under canopies and marquees (restricted size, as for gasoline service stations)	150	250	400
Pylons (as for gasoline service stations, entrance markers, etc.)	100	200	300

A considerable range is indicated in each case. The general lighting of the district as a whole and the contrast with immediately adjacent lighting, such as signs, floodlighted areas, etc., influence the brightness of the installation.

The character of the institution and the extent of the display have an important bearing on the brightness and area of the design. A place of amusement, for example, would find higher values of brightness advantageous than would be appropriate on a public building. A brightness which in a small element would capture attention and leave a pleasing impression might prove glaring and objectionable when applied to large surfaces.

Grilles and decorative patterns would seem to make greater brightness desirable because of the reduced area of the luminous source. But here care is required, for excessive brightness will result in irradiation which may obliterate much of the fine detail or change the apparent, and therefore the relative, width of the lines. So also will the swelling effect of irradiation destroy the subtle entasis of a column which is too bright.



(a) Pylon Section (b) Flooded niche (c)

Fig. 10-14.—Variation in the shape and material of the background offer an unlimited range of effects in recess elements. Tubular lamps make narrow channels possible.

Other examples of luminous architecture are shown on the following pages. Figs. 10-15 to 10-18 illustrate the lighting of two buildings at the **San Diego Exposition.** The results of the lighting are shown in Figs. 10-15 and 10-17 while the systems of producing these results are indicated in Figs. 10-16 and 10-18.

The Palace of Water and Transportation.[1]—The unusual feature of this structure Fig. 10-15 was the splendid series of cylindrical cascades of illuminated water flowing down the face of the building. The luminous colors of these waterfalls slowly changed and blended under the operation of a General Electric thyratron control.

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[1] ***Mag. of Light*, vol. 5, p. 4, January, 1936.**

At the top of the façade, the words "Water Palace" were formed of green gaseous tubes set on the faces of projecting block letters. The sculptured Indian head ornament was dimly illuminated from below by a single 60-watt inside-frosted lamp.

From the lower edges of the inverted bowl, just below this ornament, a cylindrical waterfall dropped to the basin on the marquee which contained four 400-watt General Electric underwater floodlights. These were operated on separate circuits for the four colors, red, green, blue, and amber. The lighting arrangement for each of the two cascades at the sides is shown in sketch.

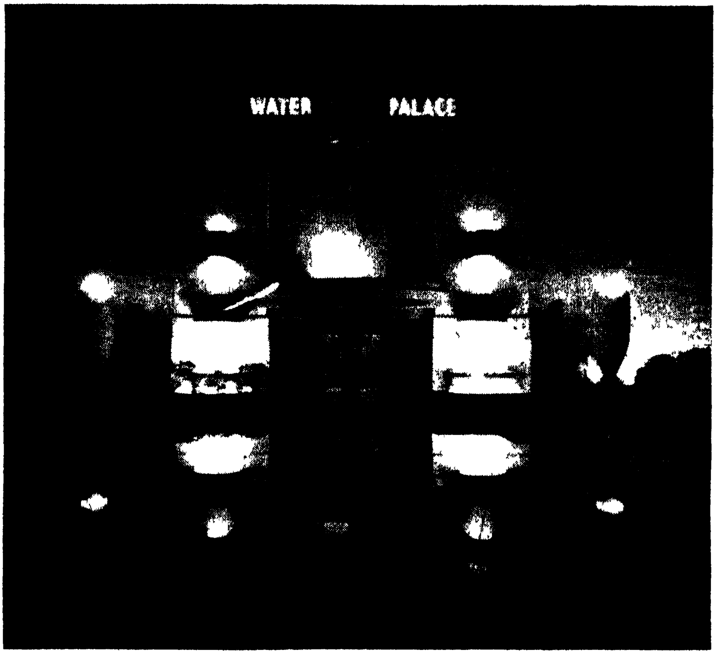

Fig. 10-15.—The Palace of Water and Transportation. (*San Diego Exposition.*)

At the tops of the huge urns, set about the large mirror pool, were flat cylindrical boxes of white diffusing glass containing four 100-watt lamps each, for lighting the courtyard. Floodlights with 1,000-watt lamps flooded the building walls in amber. The lighting details are shown in Fig. 10-16.

The Tower of the Sun.[1]—This building (Fig. 10-17) with its unique three-sided tower 108 ft. high was one of the outstanding features of the fair by night. Down the center of each face of the tower "Standard Oil" is silhouetted against a long narrow recess glowing with red light of neon tubes concealed at the sides. Powerful projectors directed upward create intricate patterns of high lights and shadows on the sculptured Mayan decorations in buff plaster. The lighting details are shown in Fig. 10-18.

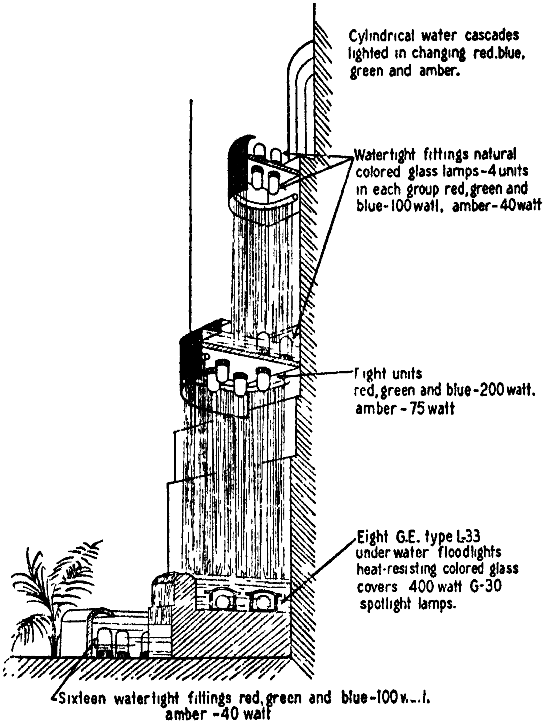
Cylindrical water cascades lighted in changing red.blue, green and amber.
Watertight fittings natural colored glass lamps-4 units in each group red, green and blue-100watt, amber-40watt
Eight units red, green and blue-200watt. amber-75watt
Eight G.E. type L-33 underwater floodlights heat-resisting colored glass covers 400watt G-30 spotlight lamps.
Sixteen watertight fittings red, green and blue-100watt. amber -40 watt

FIG. 10-16.—Lighting plan for Fig. 10-15.

A number of excellent illustrations of luminous architecture are shown in Fig. 10-19.[2] Various type of luminous signs, floodlighted surfaces, luminous store fronts, and show windows, etc., offer suggestions for improvements in the lighting of business districts.

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[1] *Ibid.*, p. 21, February, 1936.

[2] *Practical Lighting Digest*, September, 1935, General Electric Company.

Floodlighting.[1]—Modern floodlighting meets many utilitarian requirements as well as many applications concerned with decoration, aesthetic, or advertising value. Protecting property after nightfall, completing a construction job within the time allotted, illuminating a dangerous traffic intersection, and prolonging the hours of play on recreational areas are only a few of the almost infinite applications of utilitarian floodlighting.

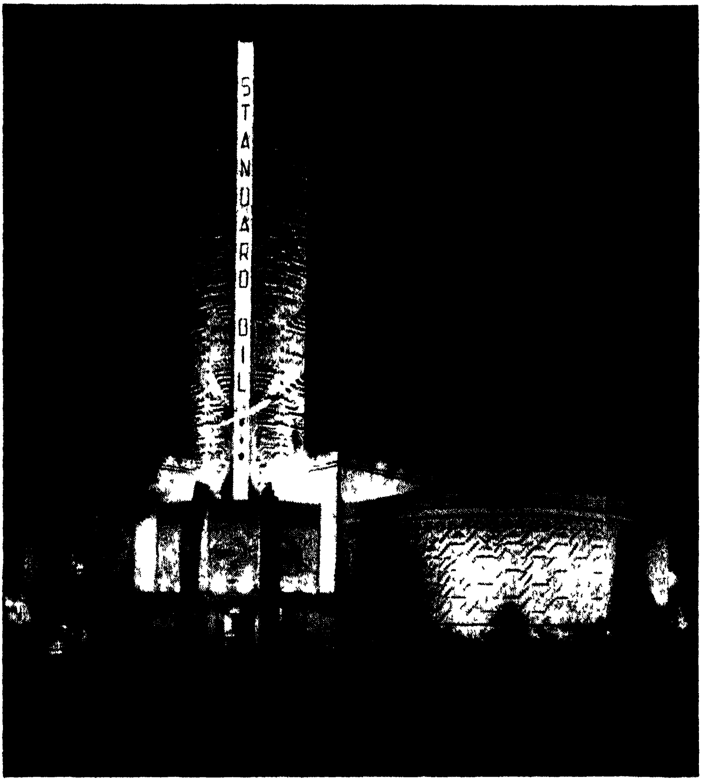

FIG. 10-17.—The Tower of the Sun. (*San Diego Exposition.*)

As an advertising medium that compels attention without detracting from the beauty or dignity of a building, floodlighting offers its best proof by the many excellent examples to be found in almost every city. The natural beauty of churches, civic buildings, monuments, and gardens is often enhanced by skillfully applied floodlighting.

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[1] HARRISON and WEITZ, *op. cit.*

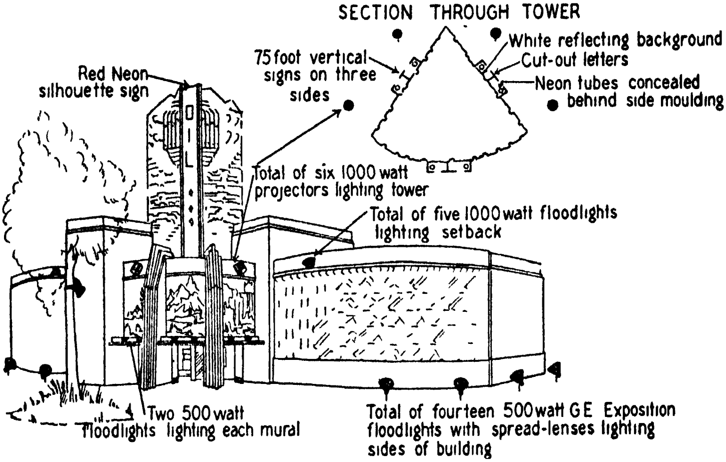
SECTION THROUGH TOWER
White reflecting background
Cut-out letters
Neon tubes concealed behind side moulding
75 foot vertical signs on three sides
Red Neon silhouette sign
OIL
Total of six 1000 watt projectors lighting tower
Total of five 1000 watt floodlights lighting setback
Two 500 watt floodlights lighting each mural
Total of fourteen 500 watt GE Exposition floodlights with spread-lenses lighting sides of building

FIG. 10-18.—Lighting plan for Fig. 10-17.

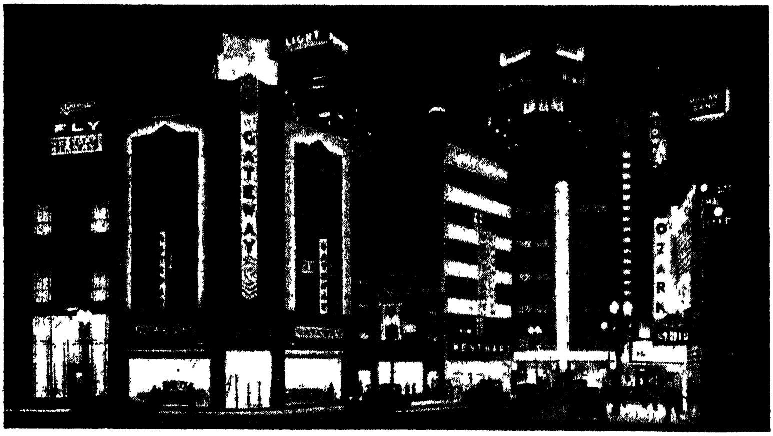

FIG. 10-19.—Examples of luminous architecture.

The lighting effect to be obtained is generally dictated by available projector locations, architectural conformation and detail, type of business or institution, surroundings, and similar considerations. As the design of a new building evolves, however, the architect may well treat night illumination not as an afterconsideration but as an integral part of the final appearance of the building—which is coming to be considered as important by night as by day. Thus the lighting effect desired dictates the provision of suitable projector locations instead of the available projector locations dictating the lighting effect.

Small buildings of simple architectural treatment are generally most effective when floodlighted with uniform illumination by projectors placed on curbposts or on buildings not more than 200 ft. away. This method of over-all illumination, free from shadows, tends to bring out the solidity, strength, and mass of the building.

Larger buildings and skyscrapers with setback features and towers offer floodlighting the opportunity to increase their apparent height and grace and to emphasize distinctive architectural features by tasteful use of shadow effects and color, if appropriate. The projectors are usually placed immediately inside and below the parapet of ledges formed by setbacks. In installations involving floodlighting of architectural or sculptural detail, the architect's viewpoint should govern.

Floodlighting of construction or recreation areas is chiefly a problem of providing light for seeing and the location of floodlighting projectors should be critically studied to eliminate glare resulting from a direct view of bright light sources in the usual field of vision.

Floodlighting with color adds to ordinary exterior lighting the increased effectiveness of brilliant colors and subtle pastel shades. Attention-compelling, high in advertising value, and aesthetically pleasing, color has been found to be a useful ally in floodlighting.

By the simple expedient of changing the colored cover glasses or filters on the projectors, a new artistry is introduced for the enhancement of buildings and monuments, fountains and gardens. Recently developed gas-discharge light sources are inherently colored and consequently produce colored light many times more efficiently than by methods of absorption necessary with incandescent lamps. Although the use of gas-discharge lamps for floodlighting is not yet widespread, their higher efficiency as a source of colored light indicates more extensive use of colored floodlighting in the future.

Floodlighting reaches its apex in beauty and effectiveness with the application of mobile color lighting. The idea of color that continually changes the aspect of buildings and fountains achieved almost immediate acceptance at its introduction, and a variety of excellent examples of this treatment are in service. The display of animated color attracts the attention and approval of everyone. With General Electric thyratron-reactor control, mobile color lighting becomes completely automatic. The striking beauty of many different color combinations can be obtained economically and can be accurately repeated in ever-changing procession without the use of cumbersome mechanical devices.

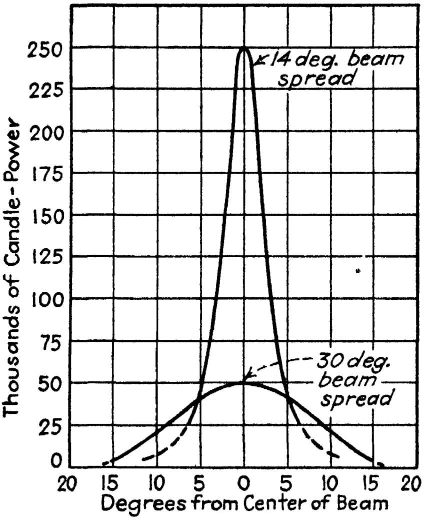

FIG. 10-20.—Typical distribution curves of floodlight projectors having narrow- and wide-beam spreads.

The design of a floodlighting installation is the summation of a great variety of widely varying factors, each of which bears an important influence upon the resultant effect. The experience of the floodlighting engineer, the effect demanded by the architect, and the numerous uses of floodlighting for many different buildings and lighted surfaces are only a few of these factors. Although much of floodlighting practice can be reduced to factual data, the experience of those designing the installation will do a great deal to determine the final result. A few hours spent experimenting with various floodlighting projectors on different surfaces at varying distances is of great value in this connection.

The lamps used in floodlights for concentrated beams of less than 15-deg. spread are usually a special floodlight lamp with a concentrated filament, a short light center length, and a round bulb of small dimensions. For spreads greater than 15 deg. general service lamps are used and are satisfactory.

The spread of a beam is illustrated in Fig. 10-20. The beam limit, generally accepted, is that point at which the beam candle power is 10 per cent of maximum.

TABLE 10-5.—FOOT-CANDLE RECOMMENDATIONS FOR FLOODLIGHTING APPLICATIONS FOR BUILDINGS*

Representative building materials‡	Initial reflection factors, per cent	Foot-candles for downtown† buildings in cities of population of		
		50,000 or over	50,000 to 5,000	Under 5,000
White terra cotta Cream terra cotta Light marble	60 to 80	10	8	6
Light gray limestone Bedford limestone Buff limestone Smooth buff face brick	40 to 60	15	12	8
Briar Hill sandstone Smooth gray brick Medium gray limestone Common tan brick	20 to 40	20	15	10
Dark field gray brick Common red brick Brownstone	10 to 20	30	20	15

* HAAS and REID, "Floodlighting," *Bull.* LD-16, 1931, Incandescent Lamp Dept., General Electric Company.

† Buildings composed of material having a reflection factor less than about 20 per cent cannot economically be floodlighted unless there is a large amount of light trim.

‡ For buildings in outlying districts use the foot-candles recommended for downtown buildings in cities of the next smaller classification.

The floodlight unit should be weatherproof and dust-tight to ensure proper maintenance.

The procedure in a floodlighting installation[1] involves:

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[1] HAAS and REID, "Floodlighting," *Bull.* LD-16, 1931, Incandescent Lamp Dept., General Electric Company.

1. A study of the best lighting effect for the project.
2. The selection of the proper foot-candle illumination. (Table 10-5.)
3. Choice of projector location from those available which will produce the best lighting effect.
4. Determine the beam spread that is correct for the projector location and the size of the area to be lighted. (Table 10-6.)
5. Determine the size and type of lamp and projector. (Table 10-7.)
6. The number of projectors may be found from the relation

$$N = \frac{\text{area} \times \text{foot-candles}}{0.70 \times \text{beam lumens}}$$

where 30 per cent is allowed for depreciation in service.

TABLE 10-6.—A GUIDE TO THE SELECTION OF THE PROPER BEAM SPREAD*

Representative floodlighting applications	Usual distance away, feet	Proper beam spread
Buildings two or three stories high, lighted from marquees or curb posts	10 to 30	Broad
Buildings lighted from across street or some distance away:		
Areas less than 3,000 sq. ft.	50 to 100	Medium
Areas more than 3,000 sq. ft.	50 to 100	Broad
Areas less than 3,000 sq. ft.	100 to 150	Narrow
Areas more than 3,000 sq. ft.	100 to 150	Medium
Areas less than 10,000 sq. ft.	150 to 300	Narrow
Areas more than 10,000 sq. ft.	150 to 300	Medium
Buildings of the setback type:		
Setbacks one or two stories high	On building	Broad or medium
Setbacks three stories high or more	On building	Medium or narrow
Columns and ornaments	2 to 10	Narrow
Construction work, parking spaces, gasoline stations, etc	At edge	Broad
Football stadiums	50 to 100	Medium

* HAAS and REID, "Floodlighting," *Bull.* LD-16, 1931, Incandescent Lamp Dept., General Electric Company.

When floodlighting the modern setback type of building the problem becomes more complicated than the preceding discussion would indicate. An analysis of such an installation by Hallman[1] follows, in which he divides a beam into 16 parts or sections, determines the percentage of light and lumens in each

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[1] E. B. HALLMAN, *Illum. Eng. Soc.*, vol. 29, p. 287, 1934.

TABLE 10-7.—BEAM LUMENS OF TYPICAL FLOODLIGHTING UNITS[*]

Beam spread	Projectors designed for floodlight lamps[†]		Projectors designed for general service lamps		
	Lamp size, watts	Average beam lumens	Lamp size, watts	Average beam lumens	
				Reflector diam. 12 to 16 in.	Reflector diam. 18 to 24 in.[‡]
Narrow			300	1,400	
	250	1,100	500	2,500	
			750	.....	5,500
	500	2,600	1,000	.....	7,800
			1,500	.....	10,500
Medium			300	1,700	
	250	1,150	500	3,000	
			750	4,900	6,000
	500	2,800	1,000	7,000	8,500
			1,500	.....	12,500
Broad			300	1,900	
	250	1,200	500	3,400	
			750	5,200	6,200
	500	2,900	1,000	7,400	8,800
			1,500	.....	13,000

[*] HAAS and REID, "Floodlighting," *Bull.* LD-16, 1931, Incandescent Lamp Dept., General Electric Company.

[†] These lamps have concentrated filaments and can be burned in any position except within 45 deg. of the vertical, base up.

[‡] These large units are recommended for long throws, or where the installation will be kept in operation for at least five years, or where there are unusually severe operating conditions.

section and from these values determines the illumination in corresponding areas on the wall.

The floodlight beam shown in Figs. 10-21 and 10-22 is that of a typical medium beam floodlight projector burning a 1,500-watt, 115-volt, general lighting service lamp. The beam lumens are 12,386 and the beam spread horizontal 22 deg., vertical 20 deg. The projector is shown located 10 ft. from a vertical surface 57 ft. 3 in. high.

From scaling the side elevation shown in Fig. 10-21 it is found that with the axis of the beam trained to make an angle of 20 deg. with the vertical the top (far) edge of the beam strikes 57 ft. 3 in. above the projector, the center of the top half of the beam 37 ft. 4 in. above, the center of the beam 27 ft. 9 in. above; the center of the lower half of the beam 21 ft. 6 in. above; and the bottom (near) edge of the beam 17 ft. 3 in. above. Measuring the areas of the sections it is found that sections 1 and 13 each cover 2.6 sq. ft.; sections 2 and 14, 14.4 sq. ft.; sections 3 and 15,

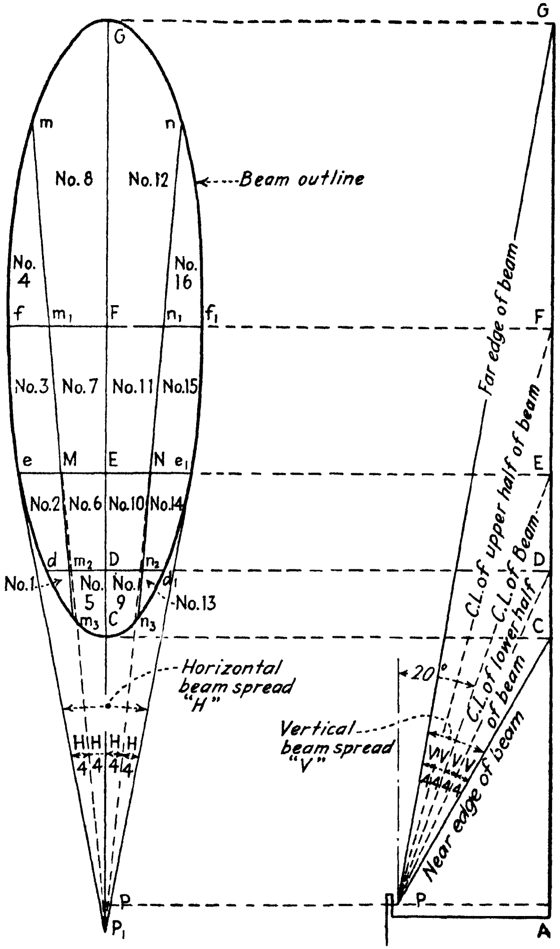


Fig. 10-21.—Beam outline on illuminated surface.

26.6 sq. ft.; sections 4 and 16, 21.2 sq. ft.; sections 5 and 9, 8.5 sq. ft.; sections 6 and 10, 16.5 sq. ft.; sections 7 and 11, 31.5 sq. ft.; sections 8 and 12, 78.6 sq. ft.

The beam proper thus lights an area of 399.8 sq. ft. Past practice has been to divide this area covered by the beam (399.8) into the lumens within the beam (12,386), calling the result the average intensity in foot-candles (31). However, knowing the percentage of beam lumens within various sections of the beam and the area covered by these sections, the average intensity in foot-candles of each section can readily be found.

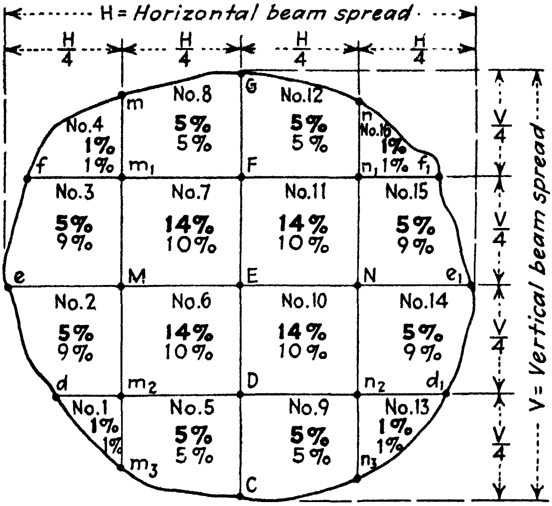


FIG. 10-22.—Distribution of light in per cent of total beam lumens.

From Fig. 10-22 the quantity of light in section 1 is 1 per cent of the beam lumens, or 123.86 lumens. The area covered by this section is 2.6 sq. ft., which indicates an average intensity over this section of 48 foot-candles. Similarly it is found that average intensities in foot-candles throughout the beam are actually as follows: sections 1 and 13, 48; sections 2 and 14, 43; sections 3 and 15, 23; sections 4 and 16, 6; sections 5 and 9, 73; sections 6 and 10, 105; sections 7 and 11, 55; sections 8 and 12, 8.

It is interesting to note that whereas the old procedure indicated an average of 31 foot-candles throughout the area covered by the beam, there is actually about one-half of this area (sections 4, 8, 12, 16) where the average intensity is only 6 and 8 foot-

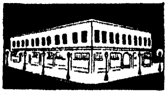
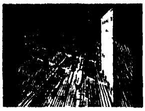
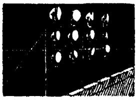
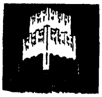
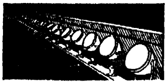
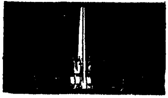
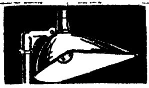
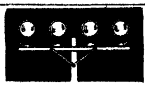
Representative floodlighting applications	Typical projectors	Distance of projector from lighted surface		Beam spread of projector	Type of lamp
a.  Buildings two or three stories high lighted from posts at curb.	Floodlights may be placed on curbposts or wide marquees to light small stores, theatres, etc., when suitable positions across the street are not available	10 to 30 ft.		Wide	General service
			Lighted surface		
b.  Buildings lighted from across street or some distance away.	 When length of building face to be illuminated is not greater than distance of floodlights from building, the units can be placed in one group.	50 to 100 ft.	Less than 3,000 sq. ft.	Medium	General service
			More than 3,000 sq. ft.	Wide	General service
		100 to 150 ft.	Less than 3,000 sq. ft.	Narrow	Floodlighting
			More than 3,000 sq. ft.	Medium	General service
		150 to 300 ft.	Less than 10,000 sq. ft.	Narrow	Floodlighting
			More than 10,000 sq. ft.	Medium	General service
c.  Buildings of setback type.	 Units are placed immediately inside and below parapet and elevated sufficiently to permit easy maintenance and avoid drifting snow.	Height of set-back	One-story	Wide	General service
			Two-story	Medium	General service
			Three-story	Medium	General service
			Four-story or more	Narrow	Floodlighting
d.  Columns, monuments.	Best projector locations are most satisfactorily determined by trial. Statues usually require light from above to avoid grotesque effect upon human features caused by light from below.	2 to 100 ft.		Narrow	Floodlighting
e. Small outdoor areas, gas stations, driveway approaches.	 Units should be mounted not less than 20 ft high and located where they will not hinder traffic or cause accidents due to glare.	At edge of area		Wide	General service
f. Large outdoor areas, parking lots, etc.	 To insure that glaring light sources will not be in the direct line of vision, it is advisable to mount projectors as high as possible.	At edge of area		Wide or medium (depending on length of throw.)	General service

FIG. 10-23.—A guide to the selection and location of floodlights. (*Illum. Design Data, page* 47, *G. E. Co. Nela Park.*)

candles. Likewise the actual maximum average intensity (sections 6 and 10) is 105 foot-candles, approximately 339 per cent of that indicated by the old method.

The design procedure followed in planning a floodlighting layout for the modern setback construction consists, briefly, in determining the effect desired, range of intensities, location of projectors, and the quantity, type, and wattage best suited to the needs.

There are many buildings where adjacent grounds are not available for the location of floodlights; neither is it possible to floodlight them satisfactorily by placing the projectors on the buildings themselves. The placing of floodlights on buildings across the street, while practical of application, involves the permission of the owner, probably a rental fee, difficulty of control, etc.

The ornamental floodlighting standard has been developed for this purpose. It consists of an ornamental street lighting post on which are placed one, or two, or three, standard street lighting lanterns. Inside the lantern are a large lamp with an adjustable reflector for floodlighting and a smaller lamp for lighting the lantern back of the reflector. This standard assists in lighting the lower part of the building and produces as well some illumination on the street and sidewalk.

These standards are placed along the curb. Better effects result if the sidewalks are wide, giving greater distance from lamp to building.

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CHAPTER XI

INTERIOR LIGHTING PRACTICE

In this chapter are represented some of the latest practices in the design of lighting installations and the applications of modern lighting equipment. Many of the illustrations were selected because of the variety of the apparatus chosen to secure the desired results as well as the diversified character of the services

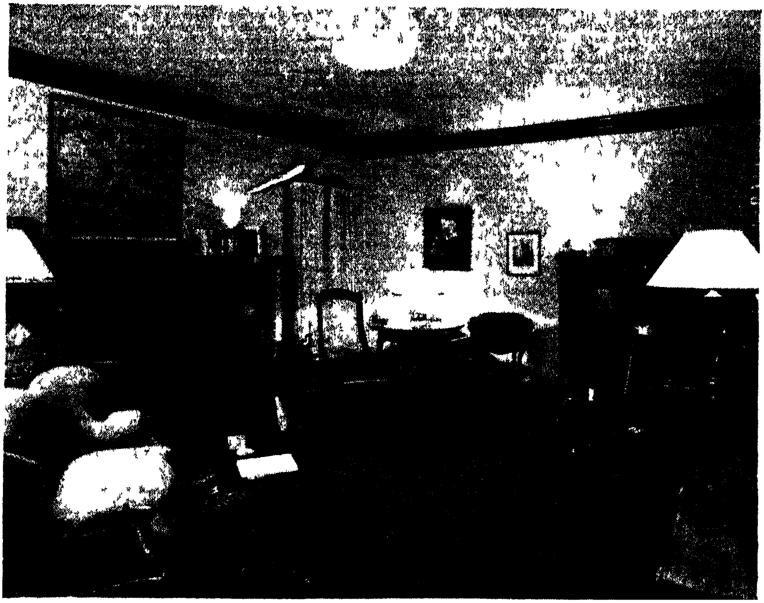

FIG. 11-1.—Living room. A modern and flexible lighting example.

The Living Room.—The living room is the scene of the social life of the home. Many activities take place here and the lighting should receive special attention. It should be flexible so that several levels of illumination may be provided—a moderate intensity for conversation and radio; a second, for reading and other visual tasks; and a third, a higher value of lighting for several tables of cards or for a social gathering. For the first, the room may be softly lighted by decorative table lamps and a general atmosphere of quiet contentment produced. Higher intensities for reading may be produced by portable lamps placed near the reader. The new types of semi-indirect and indirect floor lamps having two filaments in the bulb are especially effective in conveniently producing three different levels of illumination.

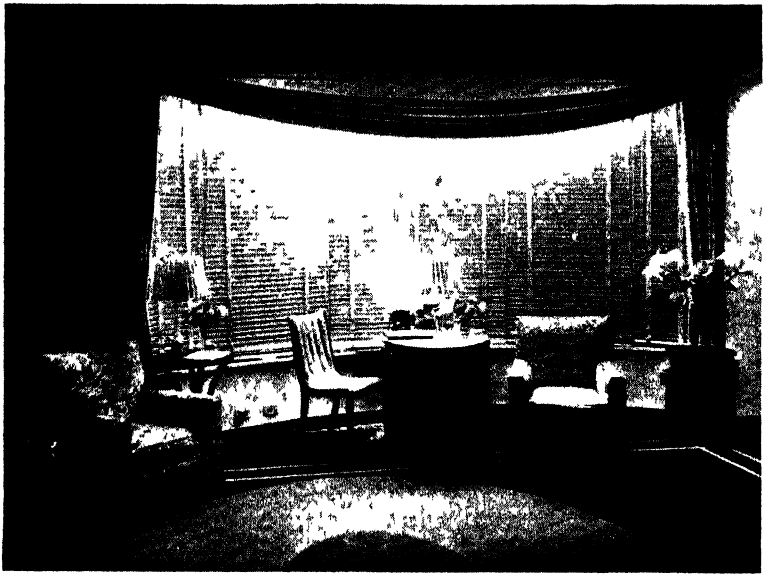

FIG. 11-2 —Living room. Indirect lighting by reflection from Venetian blinds

If ceiling fixtures are desired to produce the high intensities, the low-ceilinged room apparently maintains its size and attractiveness best with the type of luminaire which hangs close to the ceiling. Boxes, round, square, or rectangular, having good diffusing glass provide highest mounting. The close-hung ceiling cluster also serves. The high-ceilinged room allows more choice in selection since it permits also a suspension type of luminaire not suitable in the low-ceilinged room. The shaded-candle fixture or a semi-indirect luminaire may then be used.

Wall-bracket and wall-pocket units, because of their position, are sources of discomfort unless they are carefully shaded. Their purpose in a living room is chiefly decorative, the illuminating value being secondary.

An example of modernizing the lighting of a living room is illustrated in Fig. 11-1.[1] Obsolete types of table lamps and ceiling clusters were replaced by units of improved design including types of I.E.S. lamps.

Many novel and effective schemes of lighting the living room are practicable. One of these is shown in Fig. 11-2. The general lighting is indirect and from the Venetian blinds in the window area instead of the ceiling, according to general practice. The lamps are placed in efficient reflectors behind the valance and side drapes. The Venetian blinds must be very light in color—preferably light yellow.

In the illustration the draperies and lamp shades are yellow, the walls cream, and the ceiling blue.

The Schoolroom.—It is extremely important to protect the eyesight of the growing child, for injury to the eye can never be thoroughly repaired.

Daylight Illumination.—One of the fundamental rules for the proper lighting of desks is to have the preponderance of light come from the left side. For this reason many school authorities advocate *unilateral* lighting, that is, lighting by windows located on one side of the room only, especially for classrooms. This method of lighting is recommended where the rooms do not exceed about 24 ft. in width, with windows about 12 ft. high. If the rooms are much wider than this, bilateral lighting, that is, lighting by windows located on two sides of the room, may be required in order to provide sufficient illumination in every part of the room and at the same time to prevent too great a diversity of contrast in the intensity of light on the work spaces.

To secure the highest lighting value, it is recommended that the room be so designed that no working location is farther distant from a window than one and one-half times the distance of the top of the window from the floor.

Windows at the left and rear, where practicable, are preferable to those on the left and right sides of the room, because of the cross shadows created by the latter arrangement.

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[1] *Mag. of Light*, p. 24, March, 1937.

The sky, as seen through a window, is a source of glare, and so the seating arrangements should always be such that the occupants (pupils) of the room do not face the windows.

Tests of daylight in well-lighted school buildings indicate that, in general, the glass area does not fall below 20 per cent of the floor space.

As the upper part of the window is more effective in lighting the interior than the lower part, it is recommended that the windows extend as close to the ceiling as practicable.

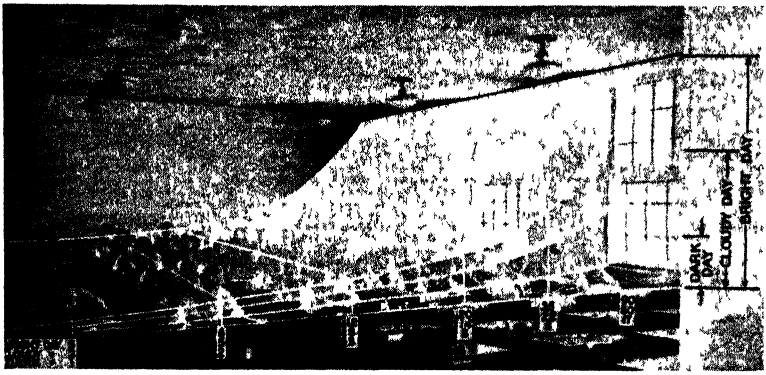

FIG. 11-3—The figures on this diagram indicate the number of units of natural illumination on desks on bright, cloudy, and dark days. They show the need of supplementing natural lighting with artificial illumination when the level falls below required minimum standards

The lighting value of a window at any given location in the room will depend upon the brightness of the sky, the amount of sky visible through the window at the given location in the room, and, indirectly, upon the reflection factor of the surroundings and the dimensions of the room.

Observations in well-lighted schoolrooms having a comparatively unobstructed horizon show that under normal conditions of daylight satisfactory illumination is usually obtained when the visible sky subtends a minimum vertical angle of 5 deg. at any work point of the room.

Where the horizon is obstructed, as by adjacent high buildings or by high trees, provision should be made for a larger window area than would otherwise be required; also, if need be, for redirecting the light into the room by means of prismatic glass in the upper sashes of the windows, or by prismed canopies outside of the windows

Although direct sunlight in interiors is desirable from a hygienic standpoint, it is often necessary to exclude or diffuse it by means of shades. These shades should perform several functions, *viz*, the diffusion of direct sunlight, the control of illumination to secure reasonable uniformity, the elimination of glare from the visible sky, and the elimination of glare from the blackboards wherever possible These requirements make it desirable to equip each window, especially in classrooms, with two shades operated by double rollers placed near the level of the meeting rail. The shades should be preferably of yellow material that is sufficiently translucent to transmit a considerable percentage of the light, while at the same time diffusing it.

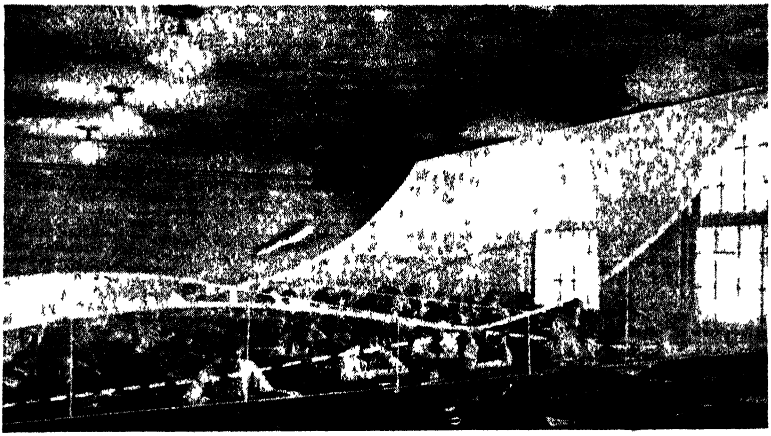

Fig 11-4 —Artificial illumination used on the darker side of the room to supplement natural lighting is economical of eyesight and of electric power.

Although the majority of schools are not used at night, it is essential that artificial light be available for supplementing daylight on dark days. A system of general illumination should be used and the lamps hung as high as possible if the direct or semidirect system be used. In most installations the units are spaced symmetrically through the room, but in the schoolroom the maximum light should come from the left and slightly forward to diminish the head and hand shadows.

Figures 11-3 and 11-4 present an interesting study of schoolroom lighting:[1] Fig. 11-3 shows typical daylight conditions and Fig. 11-4 shows the need of lighting equipment in deep rooms and on dark days.

An example of a modern schoolroom is shown in Fig. 11-5.[2] and illustrates many of the features already mentioned. The windows are high and ample. Semi-indirect luminaires, six in number, supply the artificial light. These units are equipped with three-light lamps which provide normal wattages of 200, 300, and 500 watts for each unit. The room is supplied with equipment to maintain a suitable intensity of illumination When the natural illumination falls below a prearranged minimum a photoelectric cell operates the lighting system to maintain the desired intensity. It will be seen that the blackboard lighting is provided by recessed ceiling sources.

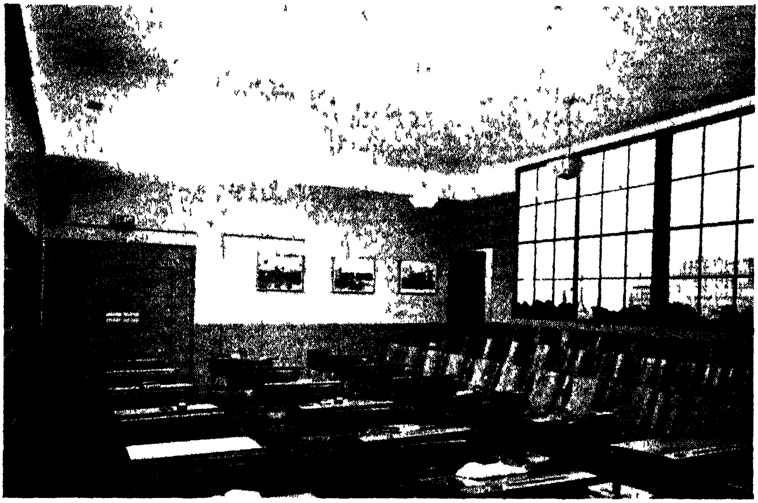

Fig. 11-5.—A modern schoolroom

The I.E.S. Lamp.—The need of an efficient portable reading and study lamp of proper design and construction received the attention of some of the members of the Illuminating Engineering Society in 1933. It was, in fact, the result of unsatisfactory conditions found in one of the large American colleges, where the lighting of the dormitories was typical dormitory lighting in general, that led to the design and specifications of the I.E.S. lamp.

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[1] *Ibid.*, vol. 4, 1935.

[2] *Ibid.*. vol. 5. p. 26. March. 1936.

The members kept in mind the need of high efficiency, an adequate amount of light downward for study and reading purposes; a spread of light of relative uniformity of from 10 to 20 foot-candles over an area sufficient for two persons; enough light above the horizontal for general illumination; and a source of low brightness in order to eliminate glare.

The result was the I.E.S. study lamp shown in the table model in Fig. 11-6. Specifications were also completed for the three-light lamp and the indirect lighting lamp.

The Illuminating Engineering Society decreed that the specifications should become generally available and the right to make the lamp accorded to all who agreed to manufacture in accordance with the specifications. A committee was appointed also to see that the specifications were incorporated in the construction and to issue certificate tags for those lamps so constructed.

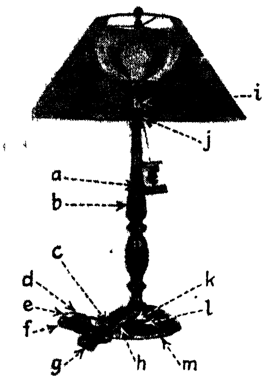

FIG. 11-6.—The I.E.S. study lamp.

This marked the first time that good engineering practices were incorporated in portable lamps. The efficiency of the average portable lamp has been increased 50 per cent, and the specifications have had the effect of improving the electrical and mechanical construction well above those usually employed before. The result has been the sale of approximately a million certified lamps per year since they were put on the market.

Some of the types of I.E.S. lamps available and the approved dimensions and suggested wattages are indicated in Fig. 11-7.[1] It is suggested that the table lamp be located on the left-hand side of flat-top desks and on large living-room tables. The floor lamp may be at the side and slightly to the rear of the lounge chair, at the end of the davenport, or to the left of the secretary, small writing table, and slant-top desk. The wall lamp may be

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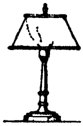
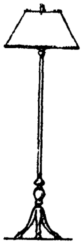
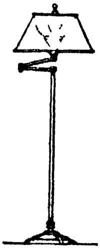
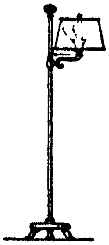
[1] *Ibid.*, p. 28, March, 1937.

Type Lamp	Approved for: Watts	Approved for: Bowl Diameter
 TABLE STUDY AND READING	100	8"
	150	9⅜"
	50–100–150 (2-filament)	9⅜"
 FLOOR STUDY AND READING	100	8"
	150	9⅜"
	50–100–150 (2-filament)	9⅜"
 SWIVEL FLOOR	100	8"
	150	9⅜"
	50–100–150 (2-filament)	9⅜"
 BRIDGE	100	8"
	150	9⅜"
	50–100–150 (2-filament)	9⅜"

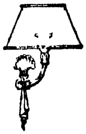
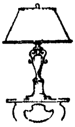
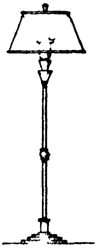
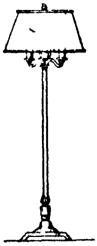
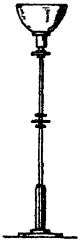
Type Lamp	Approved for: Watts	Approved for: Bowl Diam.
 WALL TYPE	100	8"
 END TABLE	100	Prismatic glass or crystal opal glass
 SEMI-INDIRECT	100–200–300 (2-filament) or 250-watt Indirect-Lite	10" 10"
 SEMI INDIRECT (WITH CANDLES)	100–200–300 (2-filament) or 250-watt Indirect-Lite Three 40-watt in candle sockets with diffusing cups	10"
 INDIRECT TORCHERE	250-watt, 300-watt, or 100–200–300 (2-filament)	Metal—various sizes

FIG. 11-7.—Types of I.E.S. lamps.

at the left of a desk; over a bed, sewing machine, chair or davenport. It may be used where light is needed and space prohibits the use of other types. The indirect *torchère* may produce general illumination.

Libraries.—The indirect lighting system is without question the ideal system for the lighting of a reading room if conditions such as a light ceiling, frequent cleaning and redecorating, etc., are practical. It is often the desire of the authorities and architects to use acoustic plaster or similar acoustic materials on the ceiling and walls and while these may be white when new they do not allow redecoration without damage to the acoustical properties.

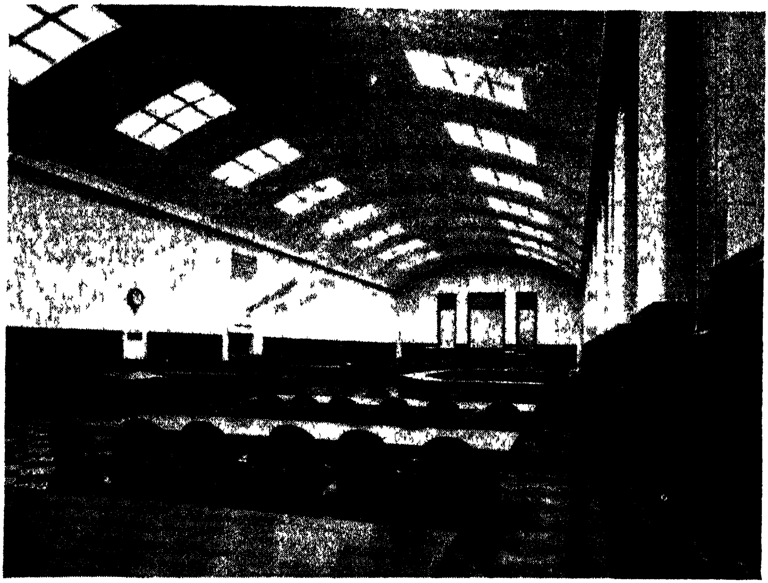


FIG. 11-8.—Main reading room of the Thomas Library in Salt Lake City.

The lighting of the main reading room of the Thomas Library in Salt Lake City, a room 45 by 192 ft., is shown in Fig. 11-8.[1] The system consists of large, flush, diffusing glass panels 6 by 9 ft. placed in the ceiling and so arranged that all cleaning, lamp replacements, etc., can be made from the attic.

This system provides a source of low brightness, allows the use of acoustic plaster on the walls and ceiling and harmonizes with the architecture of the room.

[1] *Ibid.*, vol. 5, p. 30, January, 1936.

Above each of the six sections of each panel is a white porcelain box to redirect the spill light. An R.L.M. dome reflector containing a 200-watt lamp rests upon each box. The $3\frac{1}{3}$ watts per square foot provided an illumination of 10 foot-candles shortly after completion and it is very uniform, the intensity varying but 0.5 foot-candle on the reading tables. The wiring is ample for 300-watt lamps if higher intensity is later desired.

The Office.—From the standpoint of utility the problem of office lighting can be simply stated. Fundamentally it is to provide the best illumination for sustained vision of flat surfaces in horizontal or slightly oblique planes—the angles at which papers, books, and photographs are usually examined. The perception of objects in their three dimensions, so important in the industries and in the arts, is here relatively unimportant. On the other hand, experience has shown that in offices and drafting rooms, perhaps more than in any other locations, an ample intensity of soft well-diffused light must be provided in order that discomfort may be avoided and that the eyes may not become excessively fatigued by close application for long periods of time. There should be no extreme contrast in the brightness of objects within the field of view; shadows should be subdued, if not entirely avoided; the lighting system should be designed to permit flexibility in the arrangement of office furniture; it should be easy to maintain and satisfactory in appearance.

Good office lighting provides a high intensity of illumination. For satisfactory lighting it is desirable to have the illumination on a given desk or table received from several sources. This method introduces cross lighting which tends to eliminate shadows.

The lighting of a general office with 300-watt lamps in indirect luminaries is shown in Fig. 11-9.[1] The spacing is 9 by 9 ft. The ceiling height 11 ft. The ceiling and walls are painted in two tones of cream. The initial illumination was 25 foot-candles.

An example of private office lighting is shown in Fig. 11-10.[1] Three indirect portable floor lamps equipped with three-light bulbs are used. The room is 17 by 18 ft. and a ceiling height of 11 ft. The ceiling is light cream and the walls are burnt walnut.

For private offices it is often very satisfactory to provide a relatively low intensity of general illumination by some decorative

[1] *Mag. of Light*, vol. 5, p. 31, May, 1936.

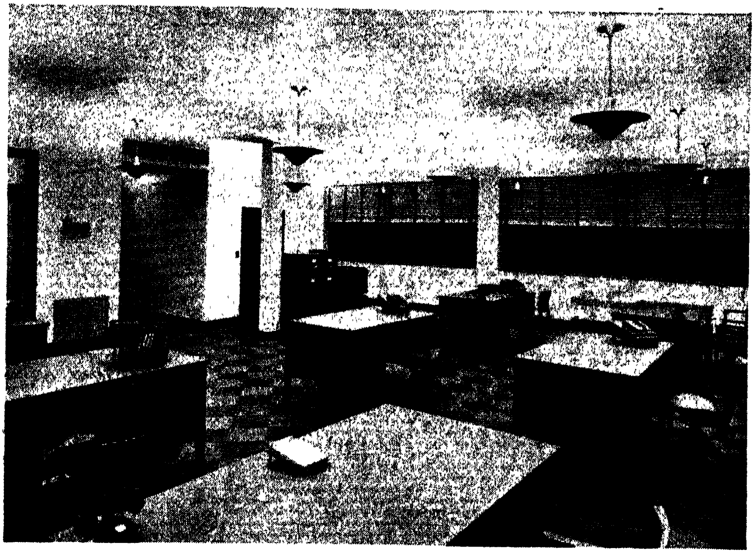


FIG. 11-9.—General office lighting. An illumination of 25 foot-candles (initial) from 300-watt silvered-bowl Mazda lamps in Silvray R.C.S. indirect luminaires.

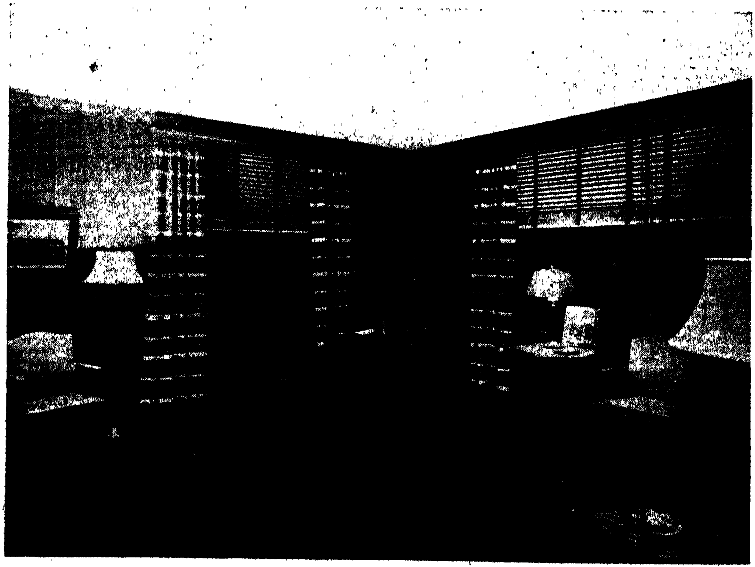


FIG. 11-10.—A private office lighted by three indirect portable floor lamps, each equipped with a Mazda three-light lamp.

central unit and use a localized light of satisfactory design for the desk. This should be located in such a manner as to prevent glaring, annoying reflections. Where glass-top desks, are used, particular attention must be paid to the type of lighting fixtures, to avoid reflections.

The Drafting Room.—Although the lighting requirements of the drafting room are somewhat exacting, they may be readily met if due care be taken in the selection and location of lighting units. The ideal condition is an even distribution of light of a high intensity well diffused. Shadows must be minimized, as they make it difficult to follow the fine lines when working close to the T square or triangle.

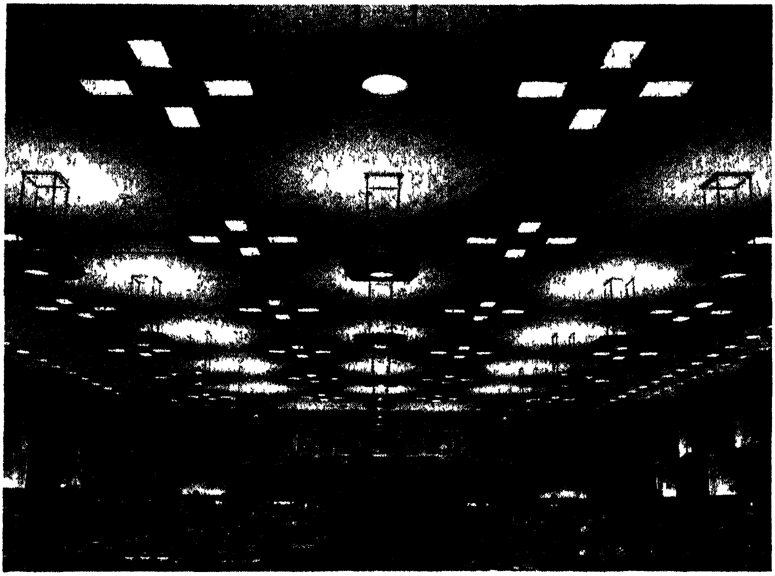


FIG. 11-11.—Main floor of the Kress Company, New York City.

The discussion of office lighting applies to drafting-room lighting. The requirements are even more exacting, as the work is particular and must be accurate. Semi-indirect systems where dense glass is employed, or totally indirect systems, are probably the best suited.

In both the direct and semi-indirect systems of illumination due note must be taken of the usual arrangement of boards relative to the windows, locating the lamps so that, as far as possible, the direction of predominant light is the same as that of daylight.

Store Lighting.—An example of modern practice in store lighting is that of the main floor of the store of the Kress Company, Fifth Avenue, New York City[1] as shown in Fig. 11-11. The room has an unbroken area of some 15,000 sq. ft. and a ceiling height of 25 ft. The illumination is produced by three systems. It will be noted that there are 18 large ceiling luminaires or hanging plaques distributed over the ceiling and grouped rather toward the center of the store. These hanging fixtures are equipped with special reflector devices to provide indirect lighting and also with an additional reflector with a 500-watt lamp and louver for direct light as well.

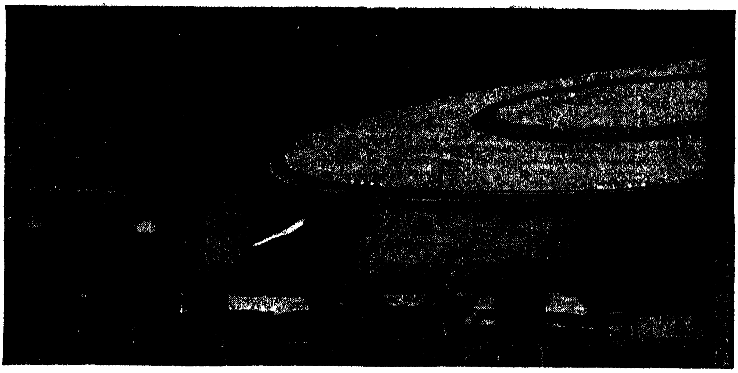


FIG. 11-12.—General view of the illumination of the table area.

There are also more than 200 recessed units in the ceiling with 500-watt lamps backed by mirrored glass projectors which direct the light through louvers of pleasing design so painted that the effect from the floor is that of glass molded into a pattern.

In the tops of locally lighted wall cases around all sides of the room are placed at appropriate locations batteries of reflectors. equipped with 500-watt lamps. These lamps contribute additional indirect lighting to the ceiling and bring into prominent view ornamental plaster plaques built into the side walls.

The illumination of the central area is 50 foot-candles, and is particularly free from glare, shadows, and bright spots.

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[1] *Ibid.*, p. 16.

Cafe lighting is exemplified by the lighting of the new Boardwalk Cafe at Jones Beach, Long Island, N. Y.[1] With the development of new forms of light-control devices the illuminating engineer has ways and means of covering definite areas with sharply controlled light of any tint or brightness desired. An excellent example of this procedure is to be seen in the installation in this cafe (Figs. 11-12 and 11-13). The room is 80 by 100 ft. and the height of the ceiling over the table is 17 ft.

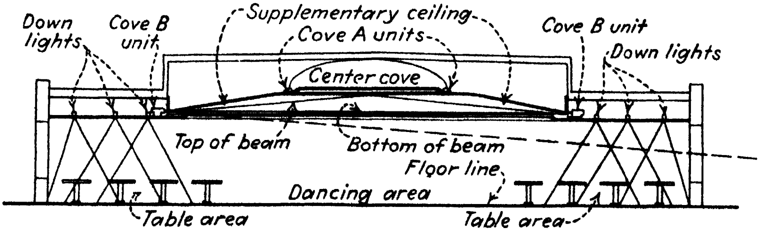

FIG. 11-13.—Section of dining room on short axis.

A sectional plan of the room is shown in Fig. 11-13. The ceiling was constructed with an inner cove and outer cove to make possible the desired lighting effects.

The center cove *A* is illuminated by 136 units spaced on 6-in. centers in alzak specular reflectors equipped with natural-colored semi-diffusing glass roundels. The four colors chosen were white, red, green, and blue. The wattage was 3,400 watts for the white, red, and green colors and 5,100 watts for the blue. The lighting units are placed in a recess around the border of the cove as shown in Fig. 11-14 and produce a smooth, uniform, highly diffused illumination over the surface of the cove.

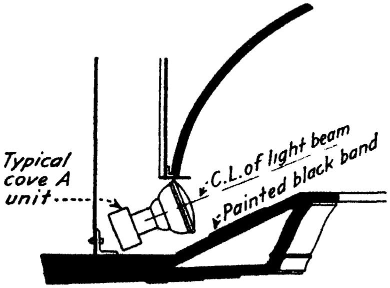

FIG. 11-14.—Detail of central-cove lighting.

The supplementary cove *B* is illuminated by ninety-six 500-watt biplane filament lamps in special units employing the principles of the klieglight, having a deep elliptical reflector, focusing shutter, blending shutter, and lens combination (Fig. 11-15). These were spaced 2 ft. on centers and divided into amber, red, green, and blue and consuming 12,000 watts per color. The units project their light through a continuous aperture, only 2 in. wide, around the perimeter or the cove (Fig. 11-16). This light passes across intervening space and illuminates the opposite surface of the cove.

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[1] *Trans. Illum, Eng. Soc.*, vol. 29, p. 559, 1934.

Four groups of four 2,000-watt projectors arranged in four colors of equal wattages are located at the lower edge of the supplementary cove. These illuminate the dance-floor area with an evenly distributed sharply defined light without illuminating too brightly the tables around the edge of the dance floor.

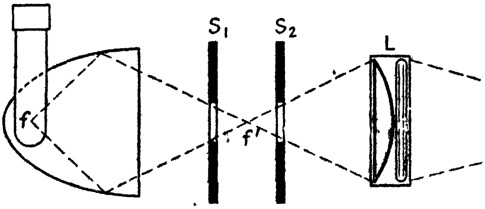

FIG. 11-15.—Optical arrangement of cove *B* lighting unit.

Six 1,000-watt projectors are directed to the orchestra platform. Four of these are used for floodlighting the platform in red, blue, green, and amber, the fifth is for the orchestra leader; the sixth unit is for the star performer and is provided with a remote-control color changing apparatus operating four natural-colored glass frames in light blue, surprise pink, amber, and magenta. The light beams from these units are projected through 6-in. diameter plaster rings located on the hidden portion of the central cove.

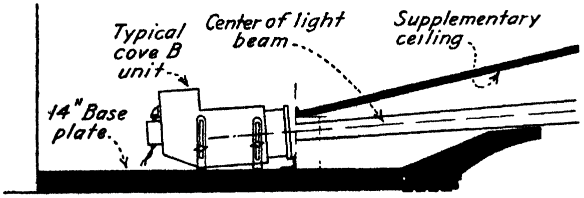

FIG. 11-16.—Detail of cove *B* lighting.

While indirect fixtures with 250-watt lamps on the pilasters are effective in creating the illusion of indirect lighting, the actual illumination for the table is from small downlights in the ceiling (Fig. 11-13).

The lamps of coves *A* and *B* and the dance floor spotlights are controlled by the thyratron-tube dimmer method. The control is arranged in such a manner that at a later date a form of automatic or color-sound control may be installed if desired.

Spectacular Lighting.—The intriguing phenomena of fluorescence and phosphorescence are rapidly finding their way into the field of decorative lighting in night clubs, theaters, and other places that may be darkened.

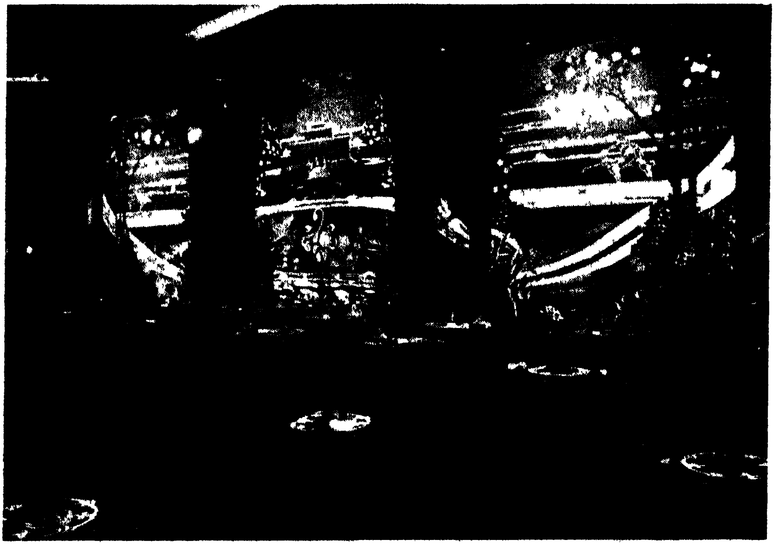

Fig 11-17 —Appearance of Club Trouville in ultraviolet light.

The possibilities of this type of lighting are illustrated in the Club Trouville (Fig. 11-17) of San Francisco.[1] Murals have been created on the walls by using fluorescent artist oils and varnishes which, although naturally colored in white light, become brilliantly luminescent when exposed to ultraviolet radiation in darkness. Each of these murals, 8 × 12 feet (Fig. 11-17), is caused to glow by a 50-inch Nico tube suspended from above.

The Nico units are of decorative design and hung from the ceiling. Thus the dance floor, dining room, and stage are flooded with ultraviolet radiation of harmless wave length and practically invisible, making possible the production of unlimited magical color effects for entertainment and decoration.

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[1] *Mag. of Light*, vol. 5, p. 28, May, 1936.

Many spectacular stunts are created by painting clever designs on the tablecloths, napkins, lamp shades, etc., with clear, colorless, fluorescent paints. These designs are invisible under incandescent light but glow in brilliant colors when the ultraviolet units are turned on and the room darkened.

A celebrant, in this club, is often startled (and perhaps deceived) to see his name and the seasonal greetings mysteriously appear in flaming green letters on his darkened tablecloth or menu. Floral centerpieces are so painted as to become fantastically colorful as the tubes begin to glow. Likewise the printed words of the menu stand out as though made of minute neon tubing.

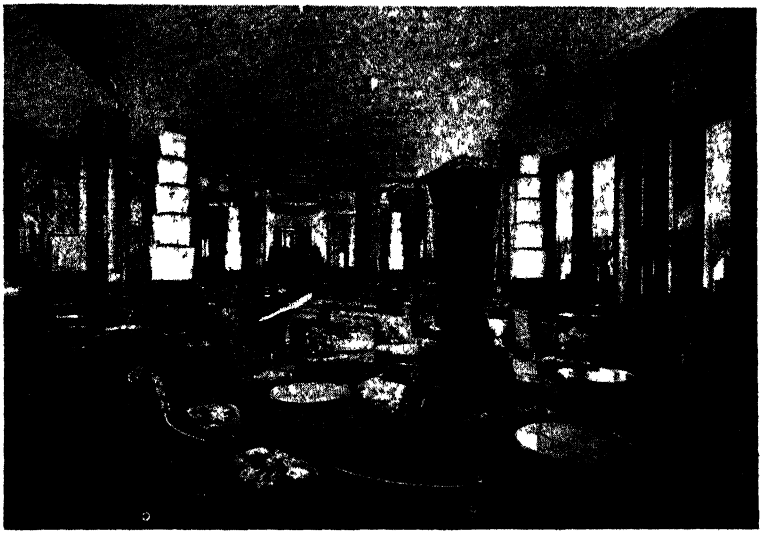

FIG. 11-18.—The Grand Salon of the steamship *Normandie.*

As a finale for floor-show numbers, ultraviolet light is used to effect an instantaneous change of costumes on the performers. Thus a group of Spanish dancers are magically transformed into beautiful fireflies in full view of the audience, or a tap dancer's body disappears, leaving only his animated shoes, hat, and gloves. It is almost unbelievable to the lighting industry as well as to the public that such striking effects are possible by the use of such a simple technique.

The *Grand Salon* on the promenade deck of the *Normandie* is a magnificent room.[1] The walls are largely of glass panels with marine scenes depicted in gold and gray. Other sections are plain with just the square, gold leaf pattern showing. The room is square. The central ceiling is white and about 25 ft. high, rounded down at the edges to the level of the alcoves to about 17 ft. The main illumination is indirect from two heavy bronze urns with a 500-watt lamp in each, under the fore and aft sections, and two rows of six luminous prism pedestals with 1,000-watt lamps in the bronze tops. To illuminate the prisms eight 50-watt, four 75-watt ordinary, and four 75-watt linolite lamps are used. Two pedestal urns with 500-watt lamps in the lateral sections are used. There are about 20 wall light ornaments concealing ventilators, each of which uses one 25-watt and two 40-watt linolite lamps. The illumination measures 5 to 8 foot-candles at the table level.

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[1] *Ibid.*, p. 22.

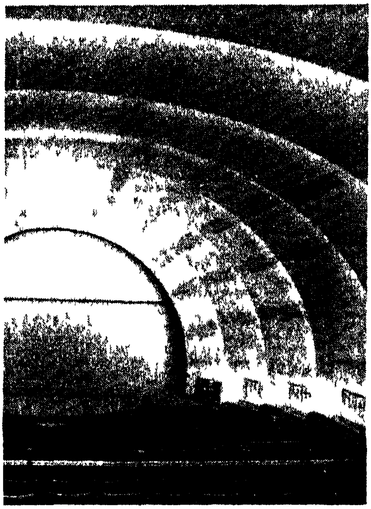

FIG. 11-19.—The auditorium, Music Hall, Radio City, New York City.

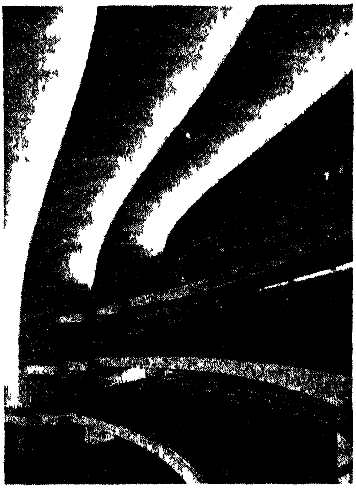

FIG. 11-20.—The auditorium, Music Hall, Radio City.

Theater Auditorium and Foyer.—Two views of the auditorium of the International Music Hall, Radio City, New York City, are shown in Figs. 11-19 and 11-20.[1] The ground floor is approximately 200 ft. wide and 165 ft. deep, and has a maximum height of approximately 80 ft. This, with the three mezzanines, has a seating capacity of 6,200. The hung ceiling consists of a series of

[1] *Trans. Illum. Eng. Soc*, vol. 28, p. 112, 1933.

eight sections slightly inclined to each other, and at the forward opening between sections or steps is placed the lighting equipment. Outlets are provided on 8-in. centers, and these are fitted with spun metal concentrating reflectors with rhodium finish. Red, green, amber, and blue glass roundels are used on the four circuits. For the first three colors 100-watt lamps are installed and 150-watt lamps for the blue circuit.

The forward sections are pierced with horizontal grilles and behind these mat aluminum reflectors with 100-watt lamps are installed on 4½-in. centers with the same color arrangement. At the front edge of the terraced extension of the stage, to be noted at the right of the first view, the same equipment is used for footlights. With the amber circuit turned on, the average illumination of the main floor is slightly less than 1 foot-candle.

On the lower side of the mezzanine floors recessed pockets at right angles to the proscenium are provided. These extend from front to rear, and lamps of the four colors are concealed in a trough reflector. The light from these is directed toward the white underside of the niche and the illumination produced indirectly. The illumination of the mezzanines varies from ½ to 3 foot-candles under the amber light.

All house and stage circuits are controlled from a thyratron switchboard placed at orchestra floor level in front of the pit.

The ceiling and sloping side walls are finished in stippled color, giving a resultant light tan effect. The stage curtain is a golden brown. The face and ceilings of the mezzanines and the front of the side terraces are in gold leaf. The seats are finished in black and upholstered in terra cotta. Each seat is provided with a recessed program light.

Space does not permit a detailed description of the elaborate lighting equipment installed on the stage which, incidentally, is 144 ft. wide, 60 ft. deep, and 105 ft. high from stage level to gridiron.

The *Grand Foyer* (Fig. 11-21) is 45 ft. wide, 140 ft. long, with a 60-ft. ceiling. There are two large pendent luminaires which are modern in design, simple and dignified in effect, slightly Viennese in feeling. They have a total length of approximately 29 ft., and an inner cylinder of heat-resisting molded glass, 16 ft. long, 2 ft. in diameter, is made in eight separate sections. This is surrounded by an outer ring of grooved glass tubes which are suspended with stainless-steel cables. Within are 98 outlets with 40-watt ivory-sprayed lamps in mat aluminum, bowl-shaped reflectors to direct the light downward. These are on five circuits. At the bottom, acting as a finial, is an indirect lighting feature in the form of a ball in which is a 500-watt lamp. A tassel of glass tubes surrounding a 40-watt tubular lamp is at the very bottom. The total weight of the fixture is approximately 2 tons, of which half is glass. The luminaires are arranged on chain block and falls so that they may be raised and lowered with ease and speed for relamping and cleaning. The design of the molded glass and tubes is such that there is a play of high light or sparkle the entire length of the fixture.

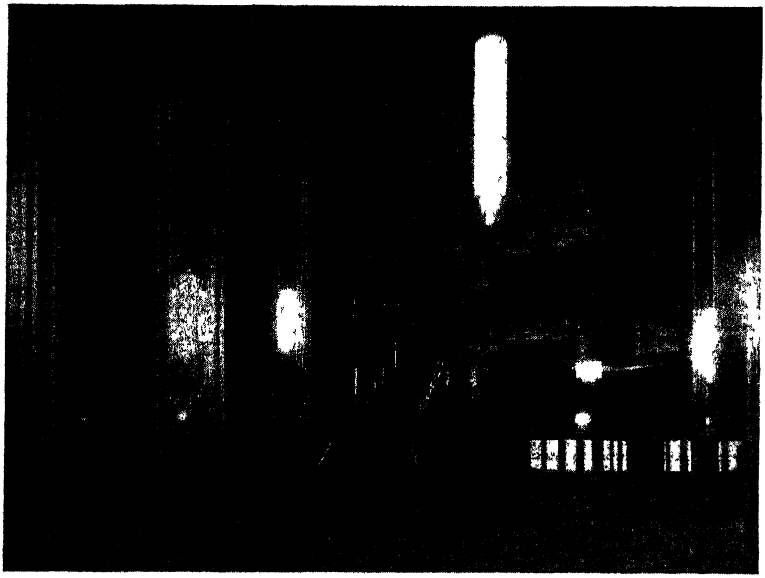

FIG. 11-21.—The Grand Foyer, Music Hall, Radio City.

The metalwork is highly polished chromium plate. There are six large wall units of the same general material. Fresnel lenses are placed in back of the center motif so that light is thrown horizontally. Each unit is designed for 1,300 watts, has an overall length of 10½ ft., and weighs approximately 950 lb. Similar smaller units are placed beneath the stairway.

The lighting equipment for this room and the luminaires are the result of many conferences on design and studies of actual models tried out in the building. The average illumination is 2 foot-candles.

Municipal Auditorium.—The lighting of the municipal auditorium of Kansas City[1] offers an excellent example of lighting large interiors. The main area is 135 ft. wide, 204 ft. long, with a ceiling height of 95 ft. The ceiling is constructed with four coves (Fig. 11-22) in which are 100-watt lamps colored red, blue, and green. There are also circular "wells" in the ceiling, each containing five 100-watt lamps in red, blue, and green. These lamps together with those in the coves provide mobile color effects, the control allowing each color to appear separately or all three colors at one time.

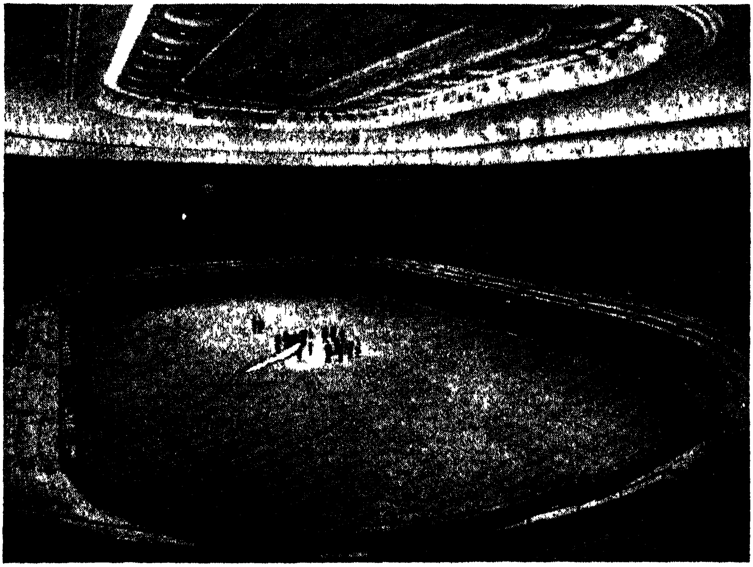

FIG. 11-22.—The municipal auditorium of Kansas City.

The general lighting for the arena is furnished by 96 floodlights equipped with 1,500-watt lamps. These units are arranged in a circular manner around the outer edge of and above the ceiling and about 3 ft. over panels of wire glass.

In the central part of the arena ceiling are 16 klieglights which give a concentrated illumination on a space about 45 ft. square directly beneath them. The klieglights are equipped with 1,500-

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[1] *Mag. of Light*, vol. 5, p. 29, February, 1936.

watt projection lamps and condensing lens and square shutters to eliminate spill light. The area thus illuminated to about 100 foot-candles may be used for a boxing ring or other exhibitions requiring high-intensity illumination. The illumination of the whole arena averages about 50 foot-candles.

Windowless Rooms and Buildings.—Air conditioning and modern lighting practice make windows no longer necessary. Inside rooms can be equipped to resemble those supplied with windows and are fully as satisfactory for commercial or industrial purposes. Fig. 11-23 shows such a room.[1]

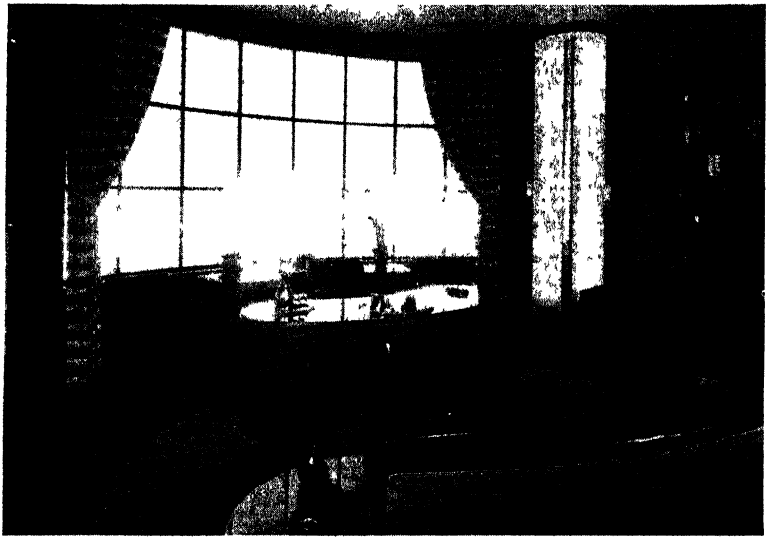

FIG. 11-23.—An indirectly lighted artificial window and indirect vertical corner coves illuminate the oval private office. The room occupies interior space and is completely air conditioned.

The windowless building is also realized.[2] The new three-story office building and printing plant of the Hershey Chocolate Company, Hershey, Pa., is built entirely without windows and in the form of a solid 350- by 150-ft. rectangle. It is equipped with modern air-conditioning and modern lighting methods.

An illumination of 20 foot-candles was decided upon and is obtained from semi-indirect luminaires equipped with a 300-watt circular mercury-vapor lamp and a 750-watt incandescent lamp. The color balance of the light is excellent, and the illumination exceeds daylight in uniformity, distribution, and constancy.

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[1] *Am. Architect*, p. 18, December, 1934.

[2] *Mag. of Light*, p. 25, April, 1936.

The lighting of the lobby of the building was designed for decorative effect rather than for high visibility or efficiency (Fig 11-24). Incandescent cove lighting was chosen. The light enters the room through glass filters of a red-orange tint. The light harmonizes with the walls and other decorative features, providing a warm tone which offsets any sense of severity in the modern decorative treatment of the room.

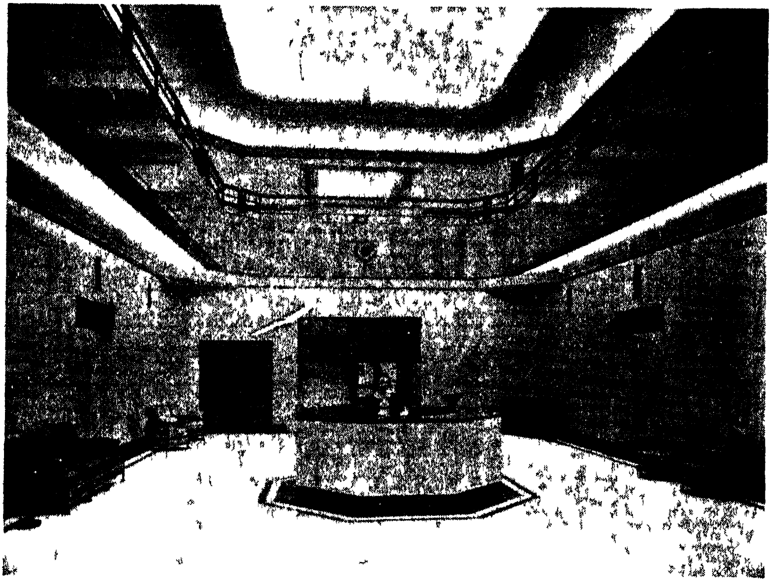

Fig 11-24 —Lobby of the windowless Hershey building

Car and Train Lighting.—The realization that passenger revenue in the future will be influenced by speed, comfort, and cleanliness has led to the streamline train, air-conditioned cars, and, among other improvements, better lighting.

Many of the new cars and trains are equipped with totally indirect lighting systems. Obviously this system gives maximum eye comfort and a pleasing appearance to the interior of the car, although the wattage required is greater and more frequent cleaning is necessary than with the direct lighting system.

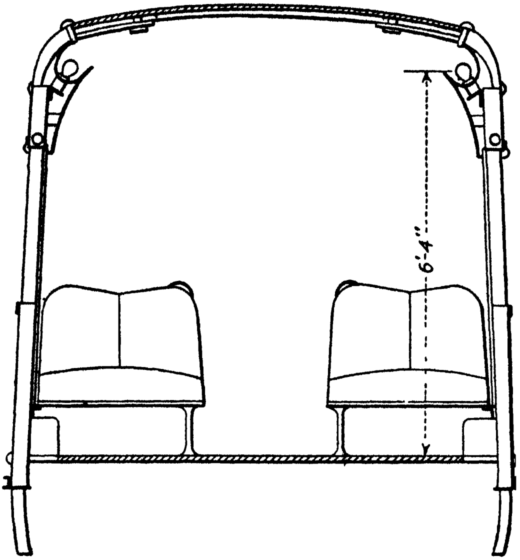

FIG. 11-25*a*.—Cross section of Chicago Surface Lines streetcar (built by Brill) showing lighting installation. Automatic cutout lamps, 1-amp., 30-volt, spaced on 11⅝ in. centers provide 4.5 foot-candles on the 45-deg. reading plane.

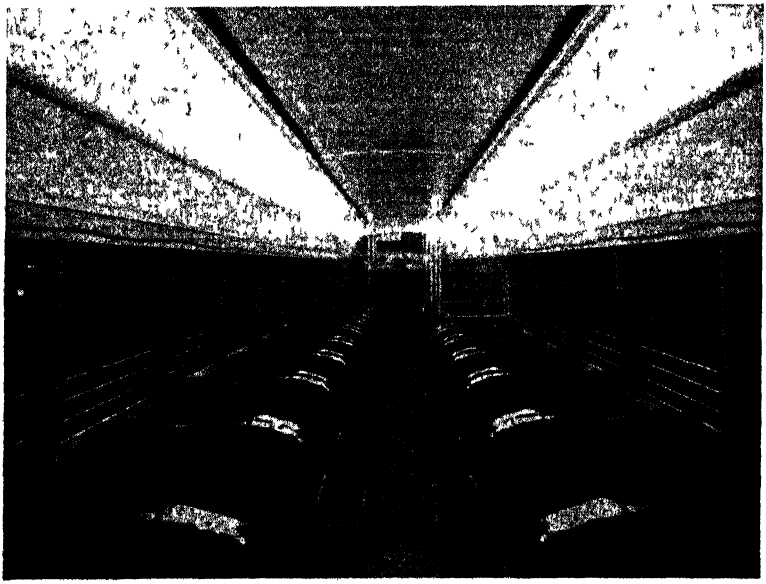

FIG. 11-25*b*.—Interior view of Chicago Surface Lines streetcar.

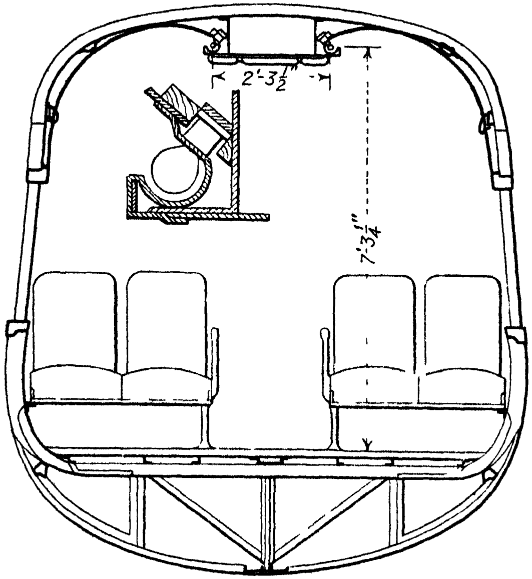

Fig. 11-26a.—Cross section of Union Pacific coach showing lighting installation. Ten-watt lamps on the 5½ in. centers provide 5.2 foot-candles on 45-deg reading plane.

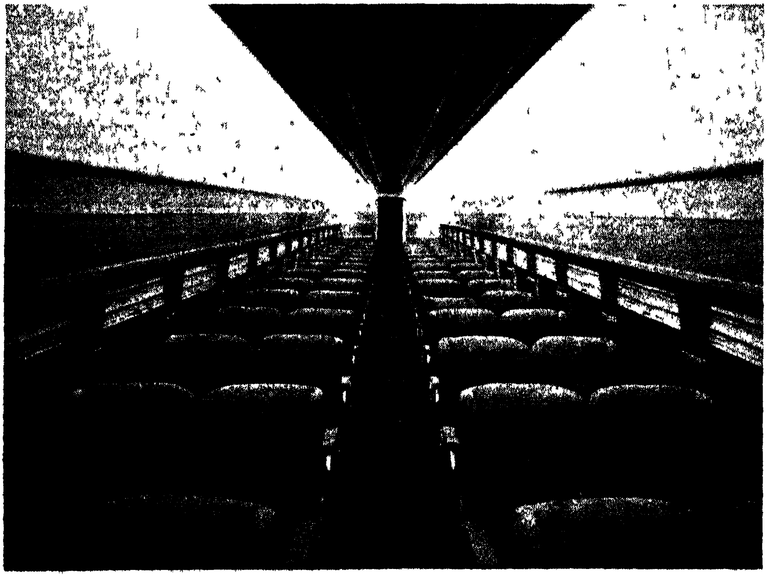

Fig. 11-26b.—Interior view of Union Pacific coach.

Following are illustrations and brief descriptions of typical types of improved lighting in light-weight cars designed for high-speed service.[1]

Electric Streetcar (Fig. 11-25).—The lighting coves are located along the sides above the advertising cards. Each cove contains thirty-one 1-amp., 30-volt, A-19, inside-frosted bulb automatic cutout lamps spaced on about 12-in. centers and mounted in a stainless-steel continuous-trough reflector. The light cream headlining with eggshell finish has a reflection factor of approximately 75 per cent and the side trim in light green has a reflection factor of about 34 per cent. The lighting circuits are designed to operate on the 600-volt trolley voltage. The average lighting intensities at the normal reading plane for all seats is 4.5 foot-candles.

Streamline Train (Fig. 11-26).—The two coves are located along the sides of an air duct mounted along the center of the ceiling. Each cove contains ninety-six 10-watt, 70-volt, S-11, clear bulb lamps spaced on 5.5 in. centers in a mat aluminum trough reflector. The ceiling which is arched on each side is finished in white, eggshell texture, with a reflection factor of about 80 per cent. The side trim around the windows is finished in buff blue with a reflection factor of about 30 per cent. The multiple lighting circuits operate at 70 volts, from a generator-storage battery system. The average lighting intensity on the normal reading plane is 5.2 foot-candles.

Other similar installations use these finishes and flat-white for metal-trough reflectors, light tan, ivory color, and eggshell, for ceilings and French gray and light blue for side trims. Observations of indirect systems on trains and streetcars indicate that they should be cleaned every two weeks.

For a system where generator capacity was limited[2] a recessed reflector unit was devised having a flush louvered door, without glass, about 8 in. square. One unit was installed over each seat. Each unit contained a 25-watt lamp used on the 64-volt service. With less than 2 watts per square foot an average horizontal intensity of approximately 4.5 foot-candles was obtained. The reflectors were of Lunax aluminum (Aezak process) semi-concentrating in design.

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[1] R. W. Cost, *Trans. Illum. Eng. Soc.*, vol. 30, p. 331, 1935.

[2] *Ibid.*

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CHAPTER XII

LIGHTING FOR RECREATIONS AND SPORTS

Recreational activities and athletic contests at night are gaining rapidly in popularity. This may be attributed to several causes. Many people are at liberty in the evening who are not free from duty in the daytime. Others might be attracted to other daytime activities, *e.g.*, golf. In the summer the lower temperature at night makes evening sports more attractive. The development of proper lighting equipment with the high-efficiency lamps now available makes sports and recreations at night under artificial light practically as satisfactory as by day.

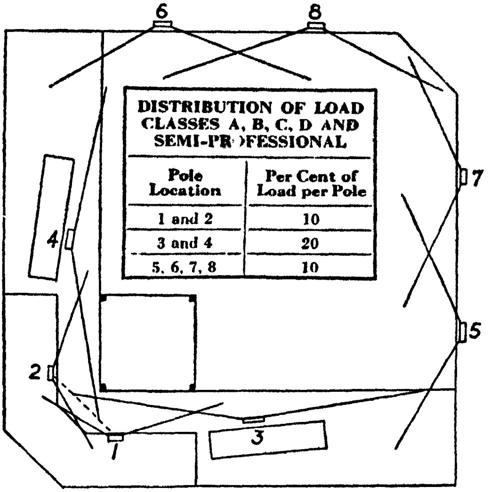
Lighting Baseball Fields.—The satisfactory light of a baseball field is the most difficult problem in athletic-field lighting. The players and the spectators as well must watch a small ball moving at a relatively high speed, which requires a high intensity of high-grade illumination for good visibility. Not only must this illumination be maintained around the field but it must also be provided to a sufficient height and of sufficient intensity that the highest ball may be followed without misjudging distances. It is also essential that annoying glare be eliminated.

To minimize glare the floodlight projectors are located high enough to be out of the usual range of vision. They should be grouped in only a few places and placed so as to light the ball evenly on all sides. Comparatively narrow-beam projectors should be used and equipped with visors to provide a sharp beam cutoff and direct the beams so that no player or spectator can look into the beam of a projector during the course of a game.

Crosley Field, home of the Cincinnati Reds, was lighted in 1935, inaugurating night baseball in the major leagues. The lighting system consisted of 364 projectors and floodlights making a connected load of approximately 1,100 kw. An average illumination of approximately 70 foot-candles was provided. The plan of the field is shown in Fig. 12-1. The 100 enclosed projectors were equipped with 1,500-watt clear lamps and the 264 open floodlights carried two 1,500 watt inside-frosted lamps. Hard-glass bulb lamps are recommended for the open floodlights to minimize breakage due to rain and sleet.

The plans for lighting baseball and softball fields of various classes are shown in Figs. 12-1, 12-2 and 12-3.[1]

In Fig. 12-1 the location of poles is shown in diagram with the approximate distribution of the load on the poles for five classes of fields. These fields generally use the open-type reflectors. Major league fields and class AA fields require a much higher illumination and better control of light. For these fields floodlighting projectors or a combination of floodlighting projectors and open-type reflectors are used. When this combination is used, about 25 per cent of the load is required in floodlighting projectors, the majority of which are placed on poles Nos. 1, 2, 3, and 4 with only a few on the other poles to light the short center field.



DISTRIBUTION OF LOAD CLASSES A, B, C, D AND SEMI-PROFESSIONAL

Pole Location	Per Cent of Load per Pole
1 and 2	10
3 and 4	20
5, 6, 7, 8	10

FIG. 12-1.—General plan of lighting a baseball field.

For softball the size of the audience, size of field, and the skill of the players are the principal factors which determine the kilowatts required.

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[1] WARD HARRISON and C. E. WEITZ, Illumination Design Data, LD-6A, Nela Park Eng. Dept., General Electric Company, 1936.

Mag. of Light, vol. 5, p. 41, April, 1936.

Open-type reflectors with 1,500-watt general service lamps are generally used, located as shown in diagram. Units on infield poles should be mounted 40 ft. high, minimum. Outfield units should be 40 to 60 ft. above ground depending on distance from home plate. See table for number of units on each pole.

Class	Load at normal voltage, kilowatts	Mounting height, feet
Major league:		
Open units*	750 to 1,000	100
Closed units*		120
AA:		
Open units*	400 to 600	100
Closed units*		120
A and B	200 to 350	80 to 90
C and D	175 to 250	70 to 80
Semi-pro	100 to 150	60 to 70

* Minimum.

Distance from home plate to outfield, feet	No. of 1,500-watt lamps on each pole			Total kilowatts
	Poles 1 and 2	Poles 3 and 4	Poles 5 to 8	
Class A (8 poles)				
150	2	3	2	27
150 to 200	2	4	3	36
200 to 240	3	5	5	54
240 to 280	4	8	6	72
Class B (6 poles)				
150	2	2	3	21
150 to 200	2	3	4	27
200 to 240	2	4	5	33
240 to 280	3	6	6	45
Class C (6 poles)				
150	2	2	2	18
150 to 200	2	2	3	21

It is recommended that lamps be burned 10 per cent overvoltage for sports lighting where the annual usage is less than 200 hr.

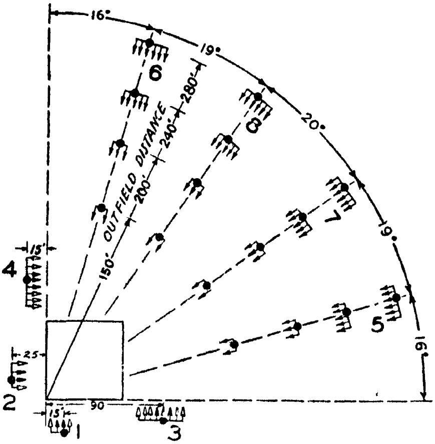

Fig. 12-2.—Plan of lighting a softball field. (Class A, 8 poles.)

Lighting Football Fields.—The lighting of a football field is not so exacting as for a baseball field. The ball is larger, moves more slowly and nearer the ground, and for the most part lengthwise of the field. In football the stands should be well lighted as there is much interest in the grandstand crowd.

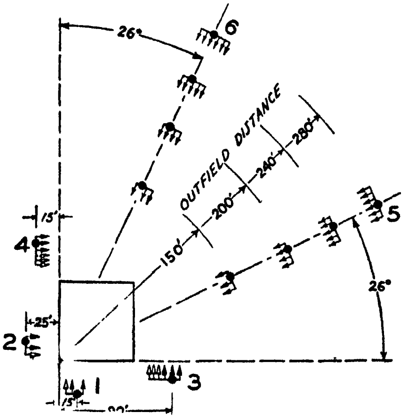

Fig. 12-3.—Plan of lighting a softball field. (Class B, 6 poles.)

Both field and grandstand can be effectively lighted by mounting floodlight projectors behind the stands and at a height of 75 to 90 ft. and so directing the beams that they will not annoy the spectators on the opposite side of the field.

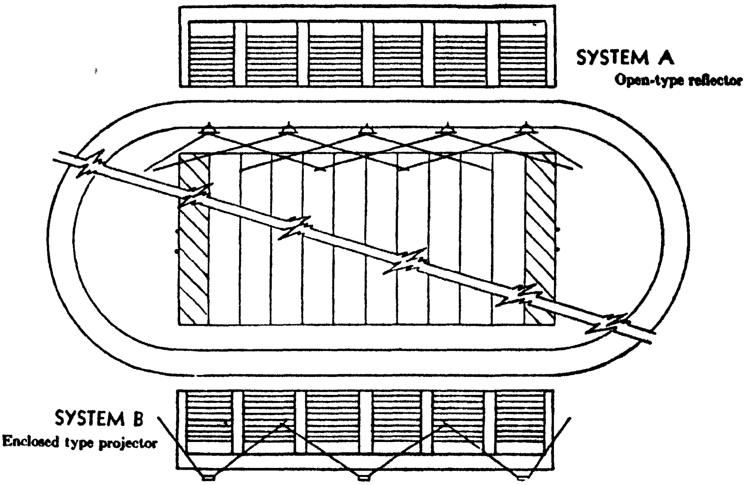

FIG. 12-4.—Plans for lighting football fields.

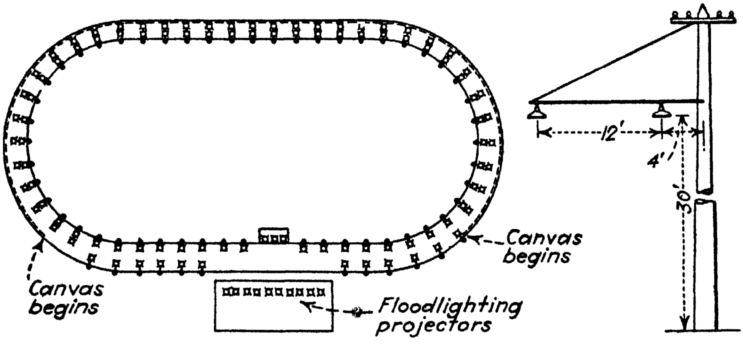

FIG. 12-5.—Lighting race tracks.

Two plans for lighting a field are shown in Fig. 12-4.[1] *A* refers to a small high-school field and *B* to the larger field referred to above.

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[1] HARRISON and WEITZ, *op. cit.*
Mag. of Light, vol. 5, p. 42, April, 1936.

A is for high schools and small colleges. Five poles are erected on each side of field, 75 ft. apart, about 45 ft. high and approximately 15 ft. from the side lines. For small schools, 5 to 6 kw. on each pole is the minimum, 6 to 12 kw. for larger schools. The size of audience and the skill of the players determine the load. Open-type reflectors are commonly used.

B is for medium-sized stadiums. Six towers, three on each side are mounted behind or in back of the stadium, 70 to 90 ft. above the playing field. The towers are spaced about 150 ft. apart with twelve to twenty 1,000-watt floodlight projectors per tower.

On the following pages are the plans and data for lighting various areas used for recreation and sports after dark.[1]

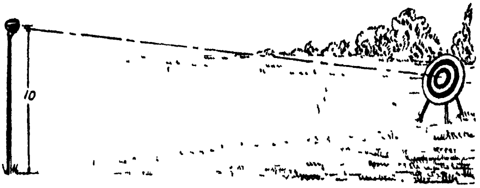

FIG 12-6.—Archery.

Race Tracks.—Sixteen-foot mast arms equipped with two 750-watt R.L.M. domes, as illustrated in Fig. 12-5, are located on the inside of the track. On the home stretch two rows of single 1,500-watt units, one on inside, one on outside of track are used. On curves and backstretch two units per mast arm are placed 4 ft. and 16 ft. out from pole. White canvas on fence is commonly used in this area to silhouette horses so that they are easily visible from the grandstand. Floodlight projectors may be placed on the grandstand, if needed, to light the track in front of the grandstand where poles would obstruct view. The recommended spacing is 50 ft.

Archery.—This increasingly popular sport requires sufficient light not only to illuminate the target satisfactorily but also to light the area surrounding the target (Fig. 12-6). Targets usually spaced about 30 ft. apart for safety.

Type of projector, one narrow beam for each target; location, directly behind and to the left of archer, mounted 10 ft. high;

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[1] HARRISON and WEITZ, *op. cit.*
Mag. of Light, vol. 5, p. 41, April, 1936.

lamp size, 250 watts for average ranges, 500 watts for longer range.

Badminton.—Because of the high flight of the bird the lighting arrangement (Fig. 12-7) must avoid over-bright light sources in the players' eyes while looking upwards. Uneven levels of illumination will cause the bird to appear to hop or change speed in flight.

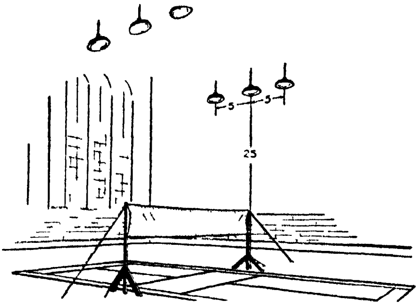

Fig. 12-7.—Badminton.

Indoor.—Type of unit, 24-in. Glassteel; location, three units 25 ft. high at each end of net; lamp size, 750 watts; 25 foot-candles recommended.

Fig. 12-8.—Bathing beach.

Outdoor.—Type of reflector, two-socket open-type mat porcelain enamel; location, one reflector at each end of net on 25-ft. poles; lamp size, 750 or 1,000 watts inside frosted; 25 foot-candles recommended.

Bathing beaches.—The swimming area as well as the beach should be illuminated. The size and type of beach determine projector locations, direction of beam, etc. (Fig. 12-8).

Type of projector, banks of narrow-beam floodlighting projectors; location, 200 to 400 ft. apart, mounted 40 to 80 ft. high; lamp size, 1,000 watts; foot-candles recommended—sufficient projectors located in each bank to provide approximately 1 foot-candle evenly distributed.

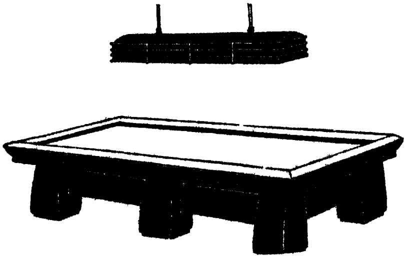

FIG. 12-9.—Billiards.

Billiards.—Type and location of reflectors, (*A*) three 100-watt deep-bowl porcelain or parchment reflectors spaced 3 ft. apart along centerline of table, mounted 5 ft. above the floor; (*B*) where an unobstructed view throughout room is desirable, a trough-type housing with lens plates or aluminum parabolic reflectors with silvered-bowl lamps may be used. Four 100- or 150-watt lamps spaced 1½ ft. apart will give good concentration of light at mounting heights up to 10 ft. (Fig. 12-9).

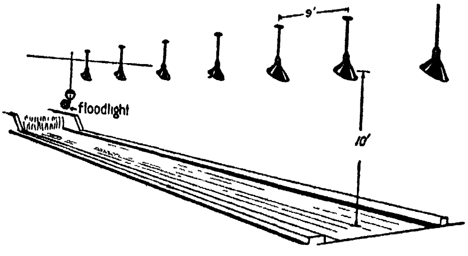

FIG. 12-10.—Bowling alleys.

Bowling alleys.—Requires good uniformity of illumination along each alley, with light sources well shielded from players. Additional supplementary floodlighting should be provided directly on the pins, usually supplied by a 200-watt projector mounted above and a little ahead of the pins (Fig. 12-10).

Type of reflector, angle type; location, 9 ft. apart on center-line of each alley and about 10 ft. above alley as illustrated; lamp size, 150 watts; foot-candles on alley 10, on pins 25.

Bowling on the green.—The court (126 ft. square, Fig. 12-11) should be fairly uniformly lighted to about 5 foot-candles and from a sufficient number of sources so as to minimize long, sweeping shadows.

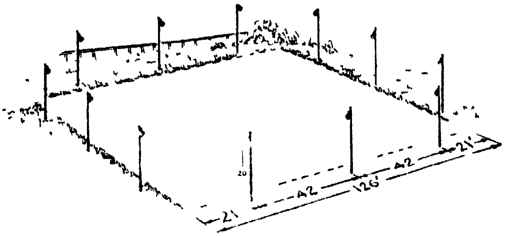

FIG. 12-11 —Bowling on the green.

Side lighting.—Type of reflector, elliptical angle; location, 21 ft. from the ends, 42 ft. apart on each of the four sides, and 5 ft. or more outside the boundaries of the green; lamp size, 750 watts; mounting height, 20 ft.

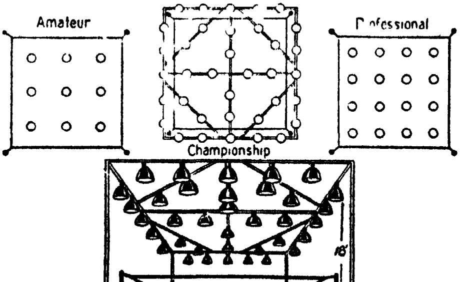

FIG. 12-12.—Boxing.

Overhead lighting.—Type of reflector, R.L.M. domes; location, 25-ft. centers, strung 25 ft. above green on messenger cables; lamp size, 500 watts.

Boxing.—The level of illumination required for boxing is indicated by such considerations as the size of the audience, the importance of the bout, and whether or not motion pictures are to be taken (Fig. 12-12).

Championship.—Type of reflector, open concentrating; location, 36 units 18 ft. above the ring and spaced as shown in sketch; lamp size, 1,000 watts; 500 or more foot-candles recommended.

Average bouts.—Nine or sixteen 1,000-watt units, according to the importance of the bout, uniformly spaced above the ring to produce 100 or 200 foot-candles. Other specifications are identical with those for championship exhibitions.

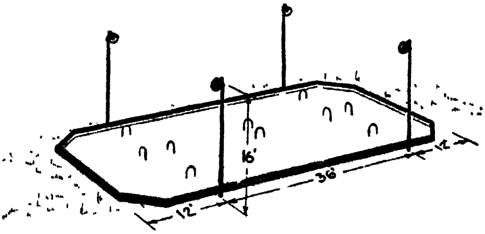

Fig. 12-13.—Croquet or roque.

Croquet or roque.—Good lighting for a field 30 by 60 ft. (Fig. 12-13) must be uniform and free from shadows for the accurate execution of difficult shots; 5 foot-candles recommended.

Side lighting.—Type of reflector, open-type angle; location, 12 ft. from the end of the court, 36 ft. apart, and mounted on 16-ft. poles, as illustrated; lamp size, 500 watts.

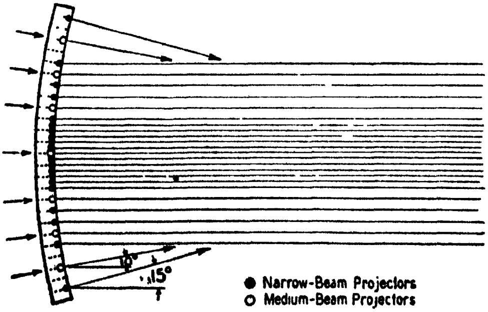

Fig. 12-14.—Golf driving range.

Overhead lighting.—Type of reflector, R.L.M. domes; location, strung on messenger cables 25 ft. above the court on 15-ft. centers; lamp size, 300 watts.

Golf driving range.—Short high shots as well as long, powerful drives must be illuminated so that players may follow the ball throughout its flight over the range (Fig. 12-14).

Types of projectors, (1) high candle power, narrow angle for long drives, (2) medium angle for short high shots; location, one projector for each tee with no less than a total of nine projectors for any driving range. About one-fourth of the units should be medium-angle projectors. Mounting height, approximately 15 ft.; lamp size, 1,000-watt for narrow-angle projectors, 1,000-watt for medium angle.

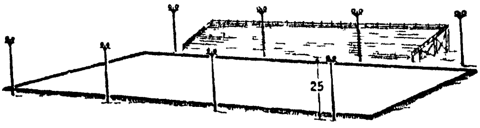

Fig 12-15 —Hockey (outdoor).

Hockey (outdoor).—The extremely fast action of hockey requires at least 10 foot-candles of illumination to enable both players and spectators to follow the puck throughout the rink. The units should be located just outside the rink to prevent slush and water from dripping on the ice and causing rough spots (Fig. 12-15).

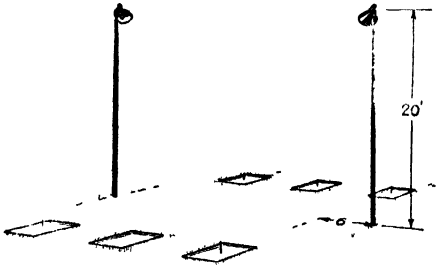

Fig 12-16 —Horseshoe courts.

Type of projector, two floodlighting projectors or open-type reflectors per pole; location, mounted at 25 ft. and spaced about 50 ft. apart; lamp size, 1,000 or 1,500 watts, 10 foot-candles recommended.

Horseshoe courts (Fig. 12-16).

For one to three courts.—Type of reflector, elliptical angle; location, on 20-foot poles, as illustrated; lamp size, 300 or 500 watts.

For more than three courts.—Place, in addition, one R.L.M. dome with a 300-watt lamp on a 20-ft. pole halfway between the pitching lines and midway between the pits of two adjacent courts.

Large groups of courts may also be satisfactorily lighted with large open-type reflectors and 1,000-watt lamps in the same relative position as shown in sketch. Ten foot-candles recommended.

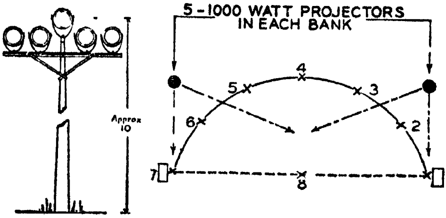

Fig. 12-17.—Skeet.

Skeet.—In skeet (Fig. 12-17) the flight of the clay pigeons is intended to duplicate the angles of flight found in actual wing shooting. Floodlighting projector beams are crossed to eliminate distorting shadows.

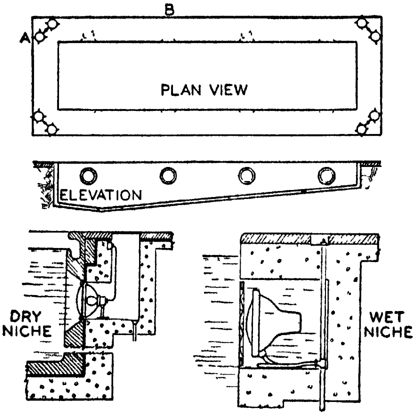

Fig. 12-18 —Swimming pool.

Type of projector, medium angle 40° spread lens; location, about 25 ft. back of shooting line at a height of approximately 10 ft.; lamp size, 1,000 watts.

Above each shooter's stand, except at station No. 8, place one 100-watt lamp in an R.L.M. dome to facilitate loading and aiming.

Swimming pool (Fig. 12-18).

For surface lighting equipment.—Two open-type floodlighting projectors, or two enclosed projectors with heavily stippled clear glass doors; location, at each corner of the pool on 25- to 40-ft. poles; lamp size, 1,000 or 1,500 watts.

Underwater lighting.—If water is sufficiently clear to see the bottom 10 ft. below the surface in daylight, underwater lighting will be satisfactory. Two classes of underwater lighting are:

1. Dry niche.—500-watt projectors with 40-deg. spread lenses, spaced not more than 12 ft. apart on each side of pool 1 to 1½ ft. below the water level. Manhole to be provided for servicing.

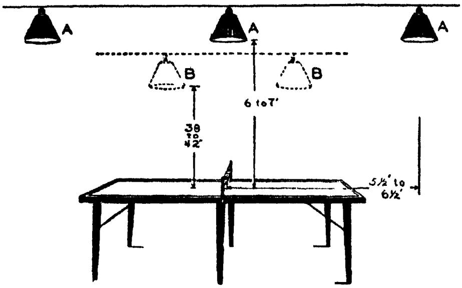

Fig. 12-19.—Table tennis.

2. Wet niche.—Same as above except that underwater equipment is necessary. The units are mounted 1 to 1½ ft. below water level. The front of niche should be protected by bull mesh. Because of the flexible hose and conductor, this type of wet niche unit makes possible cleaning or replacement of lamps without draining the pool.

Table tennis.—Lighting requirements (Fig. 12-19) are simple but for full enjoyment of the game, 30 or 40 foot-candles is needed in order to follow the small white ball in its speedy back-and-forth motion.

Type of reflector, special parchment shades with large shielding angle; location, 3 to 7 ft. above the table and spaced as illustrated: *A*, for tournament play; *B*, for recreational play; lamp size, 150 watts.

Tennis (outdoor).—For full enjoyment the light sources must be well shielded and illumination of the order of 20 to 30 foot-candles should be provided (Fig. 12-20).

Singles courts.—Type of reflector, wide angle, deep-bowl, aluminum, with skirt; location, mounted 30 ft. high on brackets with poles located as shown; lamp size, 1,500 watts for recreational play; 2,000 watts for championship.

A string of five 1,500-watt units on a messenger cable along the centerline of each court is reasonably satisfactory for recreational play.

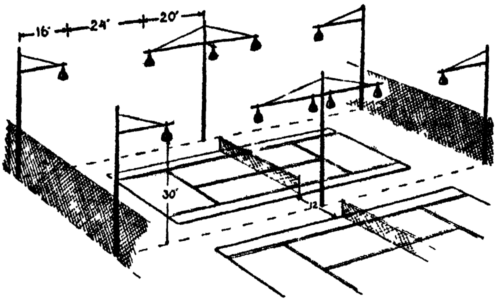

Fig. 12-20.—Tennis (outdoor).

Two or more courts.—Layout and specifications are the same as for singles courts but the inner rows require six reflectors without the shielding skirts.

Trap shooting.—Floodlighting stations are placed on either side of shooting platform (Fig. 12-21). The beams from each station are crossed to eliminate shadows. Stray light on platforms is sufficient to sight guns and to facilitate changing positions. Type of projector, eight medium-beam floodlighting projectors; location, four poles (two projectors per pole) mounted 20 to 25 ft. high behind the shooting platform; lamp size, 1,000 watts.

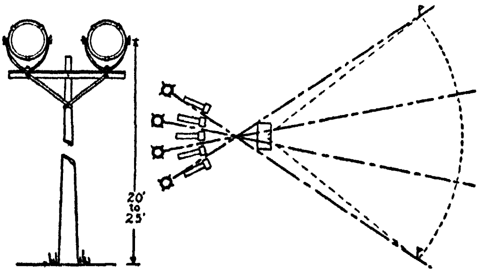

Fig. 12-21.—Trap shooting.

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"Recreational Lighting," *Mag. of Light*, vol. 5, p. 41, April, 1936.

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CHAPTER XIII

PRINCIPLES OF STREET AND HIGHWAY LIGHTING

The objects of street lighting are many. Some of these are the convenience of the public in traveling at night, the reduction of crime, speeding up traffic, increasing civic pride, and the stimulation of business and other activities which may be carried on by artificial light. More important than any of these is the lighting of streets and highways to reduce the countless number of accidents and the appalling loss of life and destruction of property caused by automobiles. With deaths in this country due to this cause numbering 38,500 in 1936 and the injuries more than a million together with the suffering and sorrow and the economic loss involved, all reasonable means of providing a remedy should be adopted. Poor street and highway lighting has been proven to be one of the major contributory causes of automobile accidents.

A thoroughly effective street lighting system is difficult to define, but when such a system is studied it will be found that the illuminants are located and placed suitably, mounted at a desirable height, and enclosed or equipped in such a way as to present to the eye a desirable combination of candle power and brightness of the lighting unit and a satisfactory distribution of light along the street and upon the buildings.

Street lighting is not merely a question of foot-candles and lamberts. Safety, quick and efficient seeing, and comfortable, adequate visibility should be the criteria in the design of a street lighting system.

Night Vision.—There are several modes of discernment exercised in street lighting. Principal among these are:

Discernment by silhouette, the object being seen in silhouette with outline wholly or partly contrasted against the background.

Discernment due to direct illumination, the intensity of illumination on the object being sufficient to permit discrimination of surface details.

Discernment by shadow, in which the presence of an object is inferred from its shadow.

Discernment by glint, the object or details of the object being perceived through specular reflection of light from some of its polished surface.

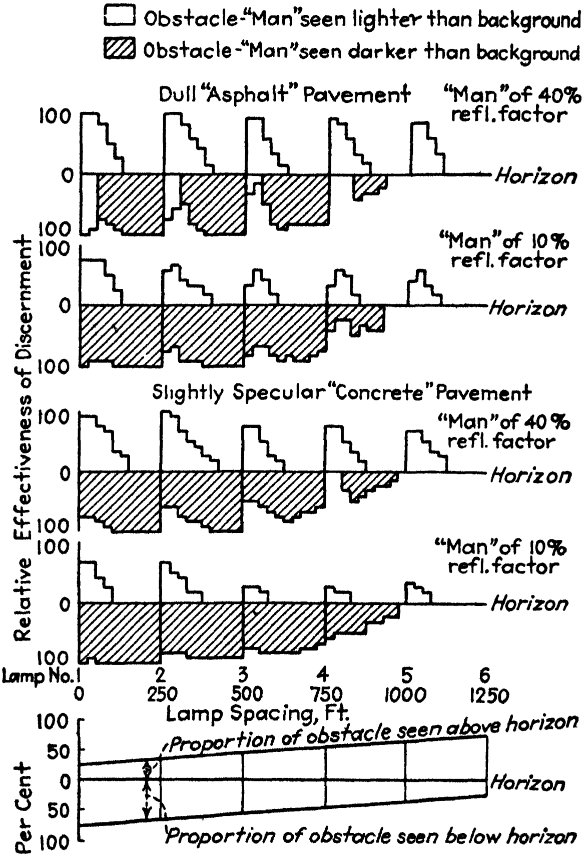

FIG. 13-1.—The importance of discernment of obstacles by silhouette on highways and streets is established quantitatively by this exploration which covers the range from bare discernment to high attention-compelling value.

A study of discernment was made by Reid and Chanon[1] on a one-eighth-scale model highway representing a highway with a 30-ft. pavement and a lighting system (B-symmetric refractor) representative of the time. The lamps were 6,000-lumen size, mounted at 20 ft., spaced 250 ft. apart in staggered arrangement, and extending 5 ft. in over the pavement. Two pavements were used, one representing dull asphalt and the other concrete with a slight oil polish. The test objects were two "men," one light gray with a reflection factor of 40 per cent and the other dark with a reflection factor of 10 per cent.

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[1] K. M. REID and H. J. CHANON, *Trans. I.E.S.*, vol. 31, p. 119, 1936. *Gen. Elec. Rev.*, vol. 38, pp. 522, 579, 1935.

In Fig. 13-1 are shown the results of this investigation. The shaded areas represent conditions under which the object is seen as a silhouette against the background. The clear areas represent discernment by light reflected by the object or perhaps reverse silhouette. The ordinates represent the relative contrast or effectiveness of the discernment at that point on the roadway weighted for that proportion of the "man" seen by the respective methods. In general it is only that portion of the "man" projecting above the horizon which is lighter than the background. This relation may be modified by the presence of traffic, trees, buildings, and elevated portions of the surrounding areas, which are disregarded in the illustration. The quantitative values of relative visibilities are the averages of three experienced street lighting engineers. Discernment by silhouette offered greater reliance and was the major method of discernment at more than 80 per cent of the locations.

Color contrast is of little use, since with intensities where discernment is at all difficult color is usually lost, and objects are perceived more readily by other means.

The majority of observations of large objects on the streets in the more intensely lighted thoroughfares, especially by automobile drivers, are as silhouettes against the bright street or building background, because a driver is concerned primarily with avoiding obstacles and usually looks carefully enough only to detect the presence of pedestrians and other objects. Usually he sees these as dark objects silhouetted against the lighter surfaces. The pedestrian, too, obtains distant views of large objects as silhouettes, but as he moves more slowly and approaches objects more closely he has opportunity for closer observation and in the more brightly lighted streets supplements discernment by silhouette with actual observation of surfaces in relief.

Illumination and Brightness.—When observing objects in silhouette the effectiveness of the illumination is its brightness in the direction of the observer rather than the foot-candle illumination on the street surface. The manner in which the street brightness seen by the observer is produced depends upon the nature of the street surface as much as, if not more than, upon the distribution of light from the lighting unit. On gravel or cement roads much of the brightness is due to diffused reflection from light-colored surfaces. The automobile headlights also illuminate the roadway for the driver.

If the pavements are asphalt surfaced or of treated macadam and as a result of automobile traffic become oiled and polished the surfaces reflect specularly. The brightness is due largely to distant lamps. The automobile headlights are of little assistance to the driver but produce a brightness due to the specular reflection in the direction of the oncoming traveler.

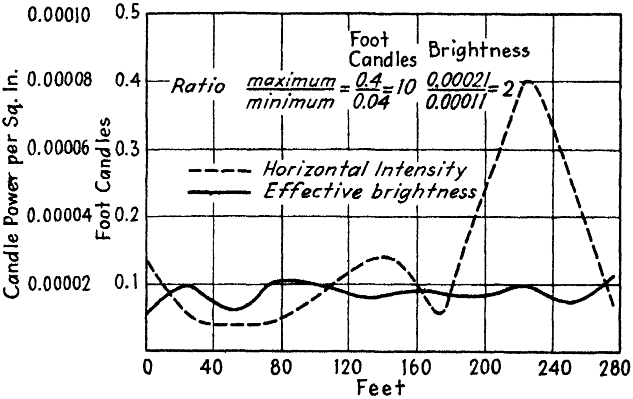

FIG. 13-2.—Showing that ratio of maximum to minimum illumination was much greater than the ratio of maximum to minimum brightness.

The horizontal foot-candle illumination on a street much traversed by automobiles was found to vary in the ratio of 10:1, while the effective brightness at the angle of the automobilist's view was in the ratio of 2:1.[1] The impression of uniformity that one receives from a trip along the street is produced by this brightness ratio rather than by the foot-candle ratio.

The illumination and brightness values on such a street are shown in Fig. 13-2.[2] It will be seen that the street surface brightness on specular streets is quite independent of distribution of illumination intensities when the street is viewed as in motoring. There are great variations in brightness along the lines transverse of the street where the illumination intensity is substantially uniform. There are substantially uniform brightness conditions longitudinal of the street where the illumination intensities vary through a wide range. Lamps in the immediate foreground which contribute most largely to the building up of illumination intensity often contribute but little to the brightness of the foreground. Where the illumination intensity is highest the brightness may be almost at a minimum, and where the illumination intensity is lowest the brightness may be at a maximum.

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[1] *Trans. Illum. Eng. Soc.*, vol. 5, p. 653, 1910.

[2] P. S. MILLAR, *Trans. Illum. Eng. Soc.*, vol. 23, p. 1051, 1928.

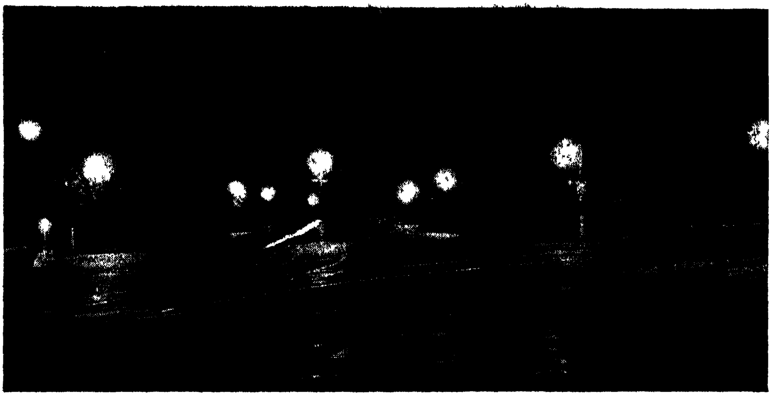

Fig. 13-3.—Lighting installation at the intersection of Cedar Road and Euclid Heights Boulevard, Cleveland Heights, Ohio.

If a specular street is wide its brightness depends upon the location of the lamps with respect to the street as well as upon the amount of light delivered upon the street. If the lamps are placed over the curbs of wide streets the streaks of light for one traveling along the street will be along the sides of the streets and the middle will appear dark. Better results will be secured by placing the lamps on brackets extending out over the street. Then the far lights will produce streaks of light near the middle of the road and the whole street surface will appear fairly bright.

It is characteristic of specular street surfaces that all of the lamps in the range of vision contribute to the brightness of the street. Each lamp produces a streak of light in the direction of the observer rendering a portion of the street surface bright and enabling it to function as a background for silhouetting (Fig. 13-3). All lamps within view, no matter how distant, contribute their elements of brightness. The brightness due to distant lamps may be as great as, or greater than, that from near-by lamps. For the traveler these bright streaks recede as he advances along the street, shortening and becoming wider as he approaches a lamp and finally disappearing to be replaced by those from another lamp farther along the street.

If streaks of light from street lamps are well distributed over the street, conditions for silhouetting are good (Fig. 13-3). In this respect two rows of lamps are better than one. A third row, *e.g.*, over a center parkway, is likely to improve conditions by increasing the number of streaks on the roadway. If the street is long and straight the distant lamps are particularly effective in providing streaks of light well out toward the middle of the street.

Lamps mounted over the curb are not nearly so effective in these respects as are lamps mounted somewhat out over the driveway. With the latter mounting and with lamps on both sides of the street the striature is likely to be excellent.

These streaks are increased in size by the crudity of the street surface. They will also be wider and longer as the size of the light source is increased, hence a large diffusing globe on the lighting unit will provide larger areas of brightness of relatively greater effectiveness in rendering the street surface bright.

A street lighting unit should, then, distribute its light so as to produce near uniform brightness. If the street surface reflects specularly the unit will be most effective if it emits much of its light just below the horizontal. To avoid glare as a result of such distribution the unit should be mounted high or to the side. It must not be forgotten that as lamps of symmetrical light distribution are mounted higher, the proportion of the light flux delivered on the street surface becomes less. This proportion is especially low if the candle power just below the horizontal is large enough to amplify the road brightness as observed from a distance. Because of this fact there have been developed two-way, four-way, and asymmetrical reflectors and refractors (described later) which are intended to deliver larger proportions of the light along the street by utilizing the light that otherwise would be wasted or used to poor advantage in other directions.

Glare.—In street and highway lighting glare may:

1. Lower the ability to see objects along the street or to perceive small contrasts.
2. Distract attention, as a result of which small contrasts may not be perceived when viewed casually.
3. Produce a temporary dazzling effect which may persist for a few moments after a bright light source is viewed directly.

The degree that glare reduces visual power depends upon:

1. The extremes of contrast within view, *i.e.*, contrast in brightness between the light source and the background.
2. The visual angle separating the glaring source from the observed surfaces.
3. The portion of the field of view which is illuminated.

In addition to the above there is the feeling of discomfort on the part of the individual and the unpleasant appearance of the installation and of the street.

If there is much light along the street, as from show windows, electric signs, etc., and especially if the building fronts are light in color, there may be little glare from street lamps and automobile headlights even though the former are placed comparatively low and are of comparatively high candle power. Also annoyance from automobile headlights is reduced because of the light in the background, and the more headlights within the field of vision the lighter the background and the less the degree of contrast. In short, anything which reduces the contrast between the glaring light source and the roadway and surrounding area, or which increases the illuminated area within view, or which separates the bright light source from the road surface reduces the effect of glare.

If the street lamp is raised to a greater height or moved to one side of the road or if the lamp is enclosed in a diffusing globe the glare is lessened. If a number of additional lamps are located beyond it along the road, the glare is further reduced. If the lamps, instead of being located over a dirt road, are located over a treated macadam road or, better still, over an asphalt road the glare is less serious.

The relationship between candle power and brightness of source and the relationship of these to location and background in street lighting are not well understood. Attempts to measure and evaluate such effects have proved unacceptable. In none of them has the subjective element been eliminated or brought under adequate control. No way has been found to reproduce for test purposes the conditions of attention which obtain in the ordinary use of the street by drivers and pedestrians, nor have means been found to evaluate the feeling of satisfaction and contentment with one lighting system which may not be experienced with another lighting system when the latter cannot be said to produce serious glare that can be measured in visual tests, but is still unsatisfactory as to brightness or candle power in the direction of the eye.

The problem resolves itself, in the main, into a means of delivering sufficient light upon a street without producing serious glare. The usual means employed are to mount illuminants at a moderate height and employ sufficiently large globes to keep the brightness below the point that produces serious glare, or else to mount the lamps high with a view to removing them from the center of the field of vision, employing some means of directing the light downward upon the street.

Good practice appears to indicate that as less light is available for streets, it becomes more important to employ equipment designed to direct it along the street, to the exclusion of the sides of the street. Conversely, when ample light is available, unnatural and dissymmetrical light distributions become unnecessary and buildings along the street may be lighted as well as the street surface with advantage with respect to visibility conditions and the appearance of the street.

When lamps of moderate or large size are mounted at relatively great distances apart, the only way to approach satisfactory lighting is to redirect the light along the street, with a large excess at angles slightly below the horizontal, in order to deliver enough light midway between lamps to render the brightness in such areas comparable with that nearer the lamps. This can be accomplished only at the expense of such high candle power and brightness at angles slightly below the horizontal as is likely to occasion serious glare at any practical mounting height.

Obviously the eyes of the observer must function efficiently if satisfactory visibility is to be obtained. To secure this, glare must be reduced to a minimum. It is astonishing how much glare reduces visibility even in a street lighting system which looks, at first sight, like a good system. Rolph[1] states that measurements have shown that at a mounting height of 13½ ft. a 4,000-lumen lamp in an opal glass globe produces a degree of glare equal to the waste of one-half of the light. The decrease in visibility is just as much a waste of light as that caused by inefficiency in light production or light distribution.

One practical means of reducing this waste due to glare is to mount the lamp at greater heights. Further measurements showed that at mounting heights of 19 and 27 ft. the glare was only one-half and one-quarter as bad as at 13½-ft.

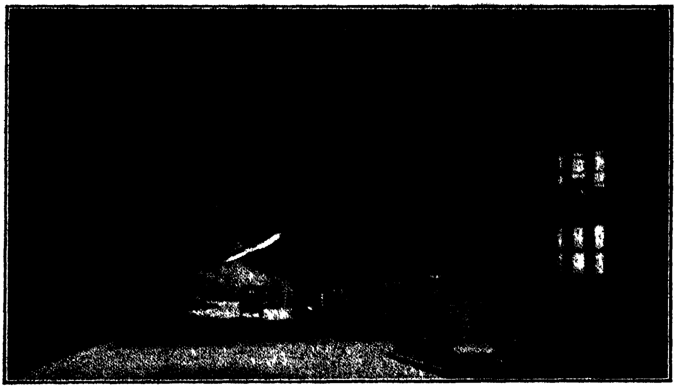

FIG. 13-4.—Street lighting by silhouette effect. Illustrating importance of bright street surface and showing how the automobile is discerned because the street surface beyond it is bright, not because the light falling upon it renders it visible. For a demonstration of glare see Fig. 13-6.

It is now well established that glare is reduced as the angle between the line of vision and the source of glare is increased. A research by SWEET[2] showed:

$$\text{Blinding effect} = K\sqrt{\text{Candle power}}$$

and for

Mounting height, feet	30	22.5	18	12
Value of K	1	1.9	3	7.3

The blinding effect being measured by the percentage of increase in illumination for equal clearness of vision compared with the illumination with conditions where blinding effect is absent and the candle power being taken as the average candle power emitted by the light unit between the 75- and 85-deg. angles. As to relative values, the same investigation showed

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[1] T. W. ROLPH, *Trans. Illum. Eng. Soc.*, vol. 26, p. 787, 1931.

[2] SWEET, *Elec. Rev. and West. Elec.*, March 6, 1915.

Mounting height, feet	30	25	22 5	20	17 5	15	12.5	10
Relative blinding effect	1	1.4	1 7	2.1	2.7	3.8	6.5	13.1

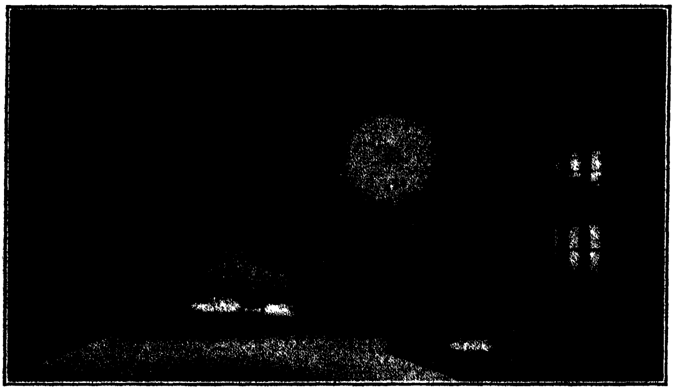

FIG. 13-5.—Same as Fig. 13-4 with nearby light source visible. For a demonstration of the importance of separating the glaring source from the observed object, hold the picture nearer to or farther from the eyes; as the distance from the picture to the eyes becomes greater the visual angle of separation becomes less and the glare effect is magnified.

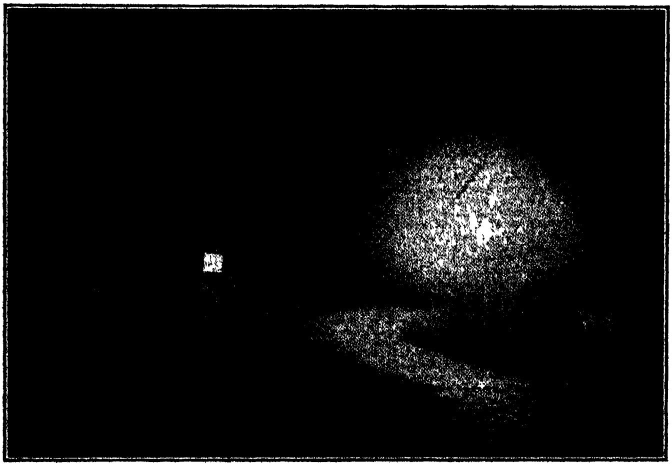

FIG. 13-6.—View of country automobile road. Lamp wrongly located on inside of curve. Glare obscures view of road beyond.

Illustrations of glare are shown in Figs. 13-5 and 13-6. In Fig. 13-4 is a very good example of discernment by silhouette. Attention is at once directed to the objects along the street and to the automobile in particular. In Fig. 13-5 the light source detracts attention from the automobile and the view is rendered less pleasant. In fact, there is a little discomfort involved in looking at the automobile. Nevertheless if one deliberately dispels the idea of the glaring source from his mind and concentrates on the automobile it can be seen just as well in either illustration. These illustrations further show the importance of adequate separation between the light source and the observed object, the distraction due to the light source being greater relatively when the picture is viewed at a distance from the eye and the visual angle between the source and the object is decreased.

Figure 13-6 shows the effect of placing a lamp on the inside of a curve. The glare obscures the road beyond.

Location of Lamps.—For effectiveness in illuminating streets, there is no location quite so favorable as directly over the driveway. Where the lamps are few and far between and of small size and where the pavement is of asphalt or other material which tends to take a polish from motor traffic, the advantages of locating the lamps over the driveway are greatest. When the lamps are numerous and of large size and the street illumination is of high intensity, the precise location of the lamps is of less importance, since the greatest revealing effectiveness does not have to be obtained from them alone.

When a relatively large amount of light is produced, effectiveness of utilization may be sacrificed somewhat to secure improved appearance. With lamps located over each curb, the street appears much wider, which is usually desirable, and the sidewalks and the fronts of buildings are better illuminated. When, however, the lighting of the roadway becomes of first importance, as in streets of the highway class, the best use may be made of the light by locating the lamps as nearly as practicable over the roadway, so as to take full advantage of all specular reflection from the street surface.

Laboratory Study of Highway Lighting.—A study of many of the features of highway lighting has been carried on by Reid and Chanon[1] using a model highway 250 ft. long built to one-eighth scale thus representing a 2,000-foot stretch of highway. Some of the results of their investigations follow:

[1] REID and CHANON, *loc. cit.*
Mag. of Light, vol. 5, p. 5, March, 1936.

1. With a representative highway lighting system objects are seen as silhouettes in over 80 per cent of the locations on the roadway. This would make it desirable to so light the roadway that all parts of it appear substantially uniformly bright when viewed from the position of driver or pedestrian. A light-colored, mat surface pavement offers the best visibility and safety at night whether the illumination is provided by street lamps or automobile headlights.

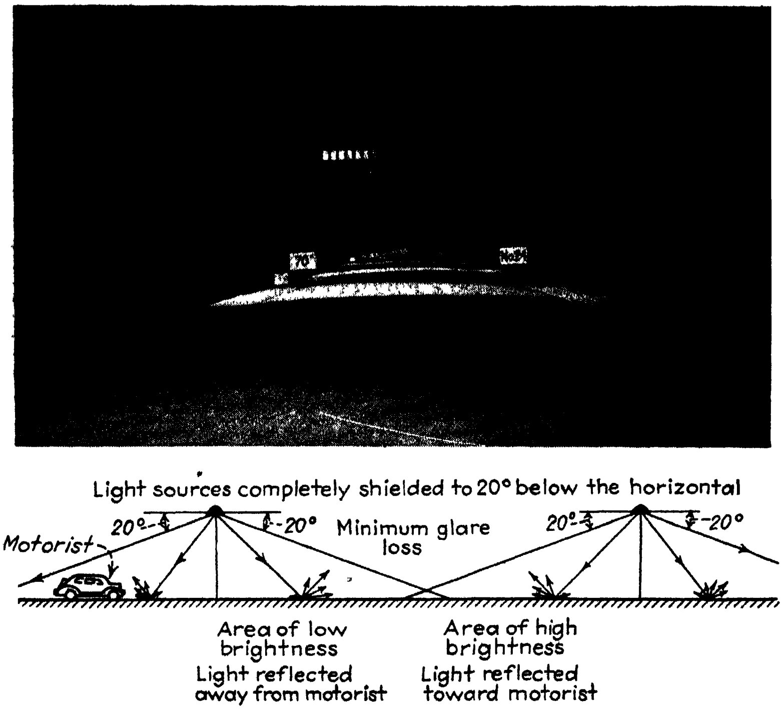
Light sources completely shielded to 20° below the horizontal
20°
20°
Motorist
Minimum glare loss
20°
20°
Area of low brightness
Light reflected away from motorist
Area of high brightness
Light reflected toward motorist

FIG. 13-7.—Pavement brightness to motorist nonuniform—ratio 8 to 1. Horizontal illumination—ratio 1½ to 1. Luminaires spaced five times mounting height—dull asphalt pavement.

2. With equal amounts of light similarly distributed from sodium-vapor, mercury-vapor and incandescent lamps, it was found that one sees objects from the standpoint of safety equally distant and just as soon with one kind of light as with the others. There appeared to be no difference between the ability to detect the presence of an obstacle and the ability to discriminate between hazards.

3. With a light distribution representative of current highway lighting practice, the glare from the equipments was found to interfere with seeing to such an extent as to waste as much as 50 per cent of the illumination.

This loss in seeing value is much greater than is generally recognized, in addition to the discomfort and distracting influence of glare.

4. A highway with a uniform horizontal illumination throughout its length, as in Fig. 13-7, presents a large variation in brightness when viewed by driver or pedestrian. For uniform brightness, as in Fig. 13-8, the light must be distributed to take account of the specular reflection of light at small angles from the surface, which is pronounced even in the case of the more mat pavements. This requires a more exact and complete control of the light flux than has been obtained with past types of highway lighting equipment. Light striking the pavement in a direction away from the observer is of little value in building pavement brightness. It is the light coming to the pavement and reflected toward the observer that is effective.

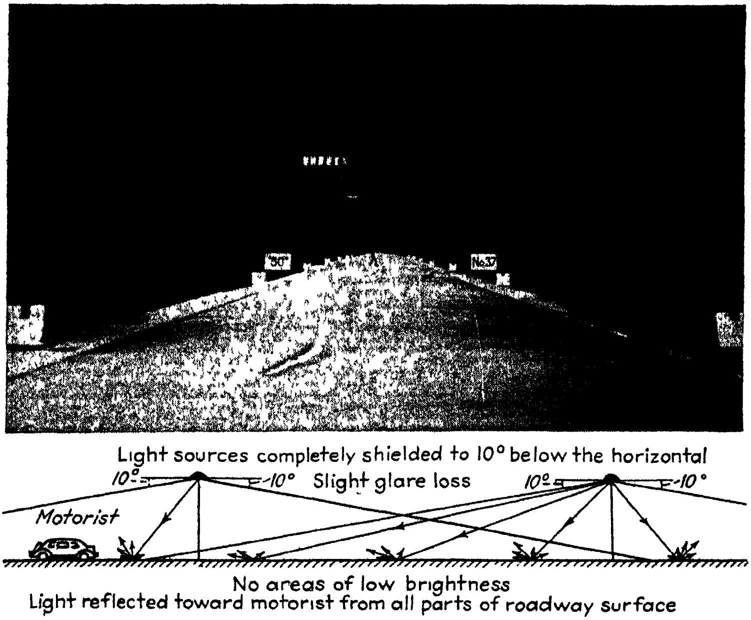
"30"
No.37
Light sources completely shielded to 10° below the horizontal
10°
10°
Slight glare loss
10°
10°
Motorist
No areas of low brightness
Light reflected toward motorist from all parts of roadway surface

FIG. 13-8.—Pavement brightness to motorist uniform—ratio 1½ to 1. Horizontal illumination—ratio 3 to 1. Luminaires spaced 5 times mounting height—dull asphalt pavement.

5. Using the standard pole spacing of 125 ft. it is feasible to obtain this high order of brightness uniformity economically and at the same time to shield the sources sufficiently to obviate, to a very large extent, the seeing loss from glare—characteristic of all past systems.

The result of these researches led to the development of an improved safety lighting system. A night view of such an installation is shown in Fig. 13-9. The improvement in seeing and safety resulting from this system are due to three special features:

1. The percentage of the light reaching the pavement is double that obtained from equipment representative of past practice.
2. Glare is suppressed by shielding the light sources to approximately 10 deg. below the horizontal.

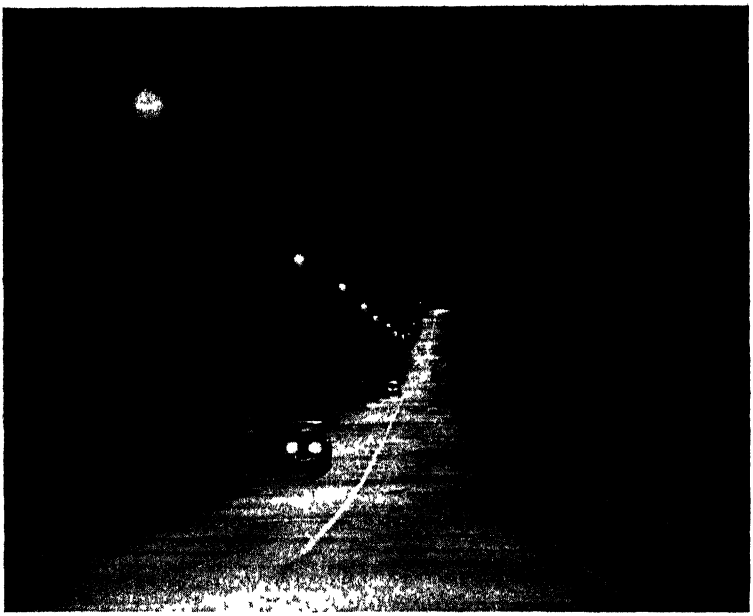

Fig. 13-9.—A night view of the system. The seeing provided and the safety achieved under this system could be equaled under representative past systems only with several times as much total light. Here one drives in comfort and walks in safety.

3. The distribution of light from the lamps is such that the road surface presents a higher order of uniformity of brightness and is free from dark areas.

The uniform brightness of the highway makes it possible to see objects quickly and surely in silhouette, and headlights are much less glaring due to the light surface.

Visibility on Lighted Highways.[1]—An instructive study of visibility on highways was made by Reid and Chanon and

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[1] Reid and Chanon, *Trans. Illum. Eng. Soc.*, vol. 32, p. 187, 1937.

VISIBILITY AND RELATED FACTORS

BALLTOWN ROAD—ROUTE 146—NEAR SCHENECTADY, N. Y.

LIGHTING SYSTEM: "Airplane" type equipments, 250 feet apart, one side, 22.5 feet high, 1.5 feet over pavement, 10,000-lumen sodium-vapor lamps.

TEST OBSTACLE: One-foot vertical disc, reflection factor 9.2%. Test locations approximately 31 feet apart, centered in traffic lanes

OBSERVERS: Seated in driver's seat of car, in center of driving lane, 200 feet from test obstacle. Eye level 56 inches above pavement.

PAVEMENT: Concrete, 20 feet wide, 4 years old, excellent condition, average reflection factor 19%.

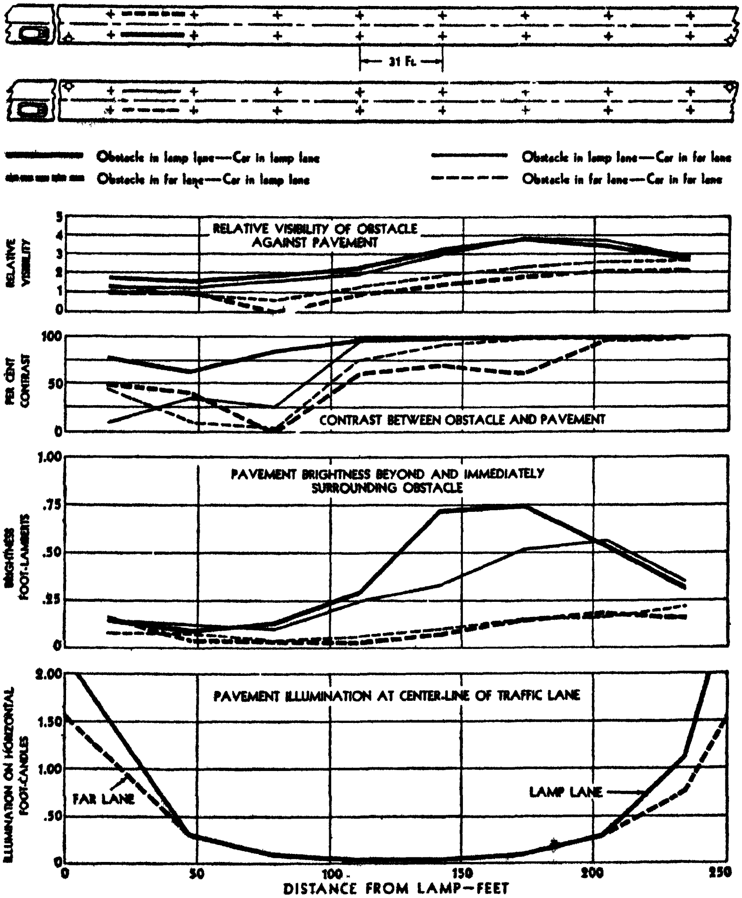

Fig. 13-10.—Measurements taken under a sodium-vapor lighting installation on Balltown Road near Schenectady, N. Y.

includes three lighting systems. The lighting system, location of units, test object, road surface, and other details together with the results of the investigation, are given in Figs. 13-10, 13-11 and 13-12. The curves show the variations in relative visibility of obstacle, contrast between obstacle and background, pavement brightness, and foot-candles on the horizontal.

In all the charts it will be noted that the visibility of the test obstacles was found to be generally highest, as would be expected, where both observer and obstacle were in the lamp lane (heavy solid line). Under the other conditions the obstacle visibilities were of lower orders. At certain points, with the systems employing 250-ft. spacings, the obstacle visibility was dangerously low. With these systems a staggered arrangement would undoubtedly tend to raise the low-visibility points appreciably.

The pavement brightnesses are plotted in terms of foot-lamberts. These readings are of direct significance inasmuch as they are related to the visibility of the road surface itself. Reasonable uniformity of pavement brightness, particularly with freedom from areas of low brightness, is generally recognized to be the ideal from the standpoints of driving comfort and assurance as well as safety.

It is an oft-recorded observation that a so-called diffuse pavement is not actually diffuse where the angles of incidence and of observation are relatively grazing, as in highway and street lighting. This is again shown quantitatively by the differences between the readings of foot-candles and pavement brightnesses with the systems having 250-ft. spacings. Light striking the pavement in a direction *away from* a motorist is of little value in building pavement brightness. It is the light coming *toward* the observer which is effective in making the pavement appear bright. It should be noted in Figs. 13-10 and 13-11 that the pavement brightness *beyond* a lamp is relatively low. This is true in spite of the fact that these luminaires emit a substantial amount of light at the horizontal and just below. Such a distribution of light is sometimes considered as justifying completely a relatively wide spacing. However, it is obvious from the curves that a materially lower ratio of spacing to mounting height would be much better practice.

The readings of obstacle visibility under the three systems are for the most part consistent with the corresponding values of

VISIBILITY AND RELATED FACTORS

BALLTOWN ROAD—ROUTE 146—NEAR SCHENECTADY, N. Y.

LIGHTING SYSTEM: 11-inch rippled-bowl, B-symmetric refractors, 250 feet apart, one side, 22.5 feet high, 4 feet over pavement, 10,000-lumen incandescent lamps.

TEST OBSTACLE: One-foot vertical disc, reflection factor 9.2%. Test locations approximately 31 feet apart, centered in traffic lanes.

OBSERVERS: Seated in driver's seat of car, in center of driving lane, 200 feet from test obstacle. Eye level 56 inches above pavement.

PAVEMENT: Concrete, 20 feet wide, 4 years old, excellent condition, average reflection factor 19%.

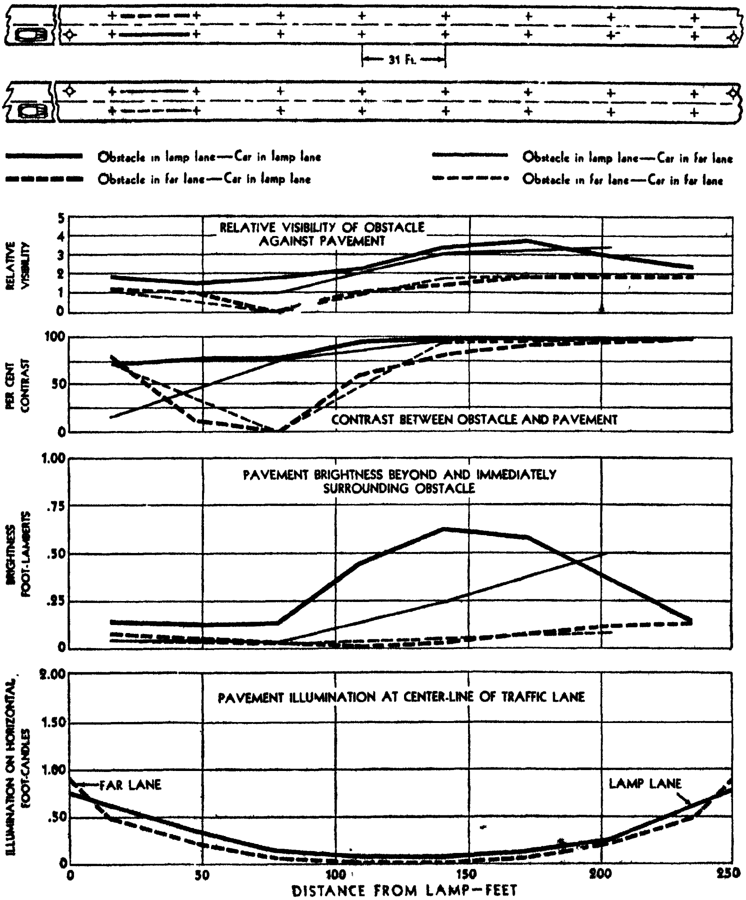

FIG. 13-11.—Measurements taken under incandescent lighting with refractor equipment on Balltown Road near Schenectady, N. Y.

pavement brightness and obstacle contrast. The other two factors in seeing—time and size—are not present here because no time limit was placed on the visibility observations and all readings in the main series were taken at the 200-ft. distance.

In Figs. 13-10 and 13-11 the points of particularly low contrast were those at which the test obstacle was seen as lighter than the background or approached this condition. At all other points the obstacles were seen as silhouettes.

In Fig. 13-12 the pavement brightness is higher when measured from the far lane toward the lamp lane than when measured along the lamp lane. The reason is that these luminaries were designed to direct more than half of the light across to the opposite lane in order to maintain its brightness for drivers in the far lane.

The visibility of obstacles on the roadway is the most important single factor in seeing for safety. A comparison of the obstacle visibility under different lighting installations is therefore of particular safety significance. In such a comparison one is interested in both the average and the minimum visibility values.

The two installations on the Balltown Road lend themselves to direct comparison of obstacle visibility. Here the only variables affecting visibility are the difference in light distribution and the less favorable transverse position of the sodium luminaires. The difference in spectral quality is not a significant factor in the visibility of substantial objects.

Under the conditions of the main series of tests here reported the average relative obstacle visibilities were found to be 2.01 for the sodium and 1.78 for the incandescent installation on the Balltown Road.

A determination can be made of the changes in lamp lumens which would produce in the different installations the same average obstacle visibility. This is possible because of the data obtained in the model-highway researches on the changes in visibility resulting from changes in lamp lumens. Over 10,000 observations showed that at brightness levels representative of good highway lighting practice an increase in lamp lumens produces one-third as much increase in visibility.

Comparing quantitatively, then, the two installations on the Balltown Road, the sodium provides 15 per cent higher average obstacle visibility than the incandescent installation. To pro-

VISIBILITY AND RELATED FACTORS

CHAGRIN BOULEVARD—U. S. ROUTE 422—NEAR CLEVELAND, OHIO

LIGHTING SYSTEM. New shielding type of reflector equipments (G-E Form 86), 125 feet apart, one side, 25 feet high, 5 feet over pavement, 4000-lumen incandescent lamps.

TEST OBSTACLE: One-foot vertical disc, reflection factor 9.2%. Test locations approximately 31 feet apart, centered in traffic lanes.

OBSERVERS: Seated in driver's seat of car, in center of driving lane, 200 feet from test obstacle. Eye level 56 inches above pavement.

PAVEMENT. Concrete, 20 feet wide, 8 years old, some bituminous patch areas and marked discoloration from oil and tar, average reflection factor 16%.

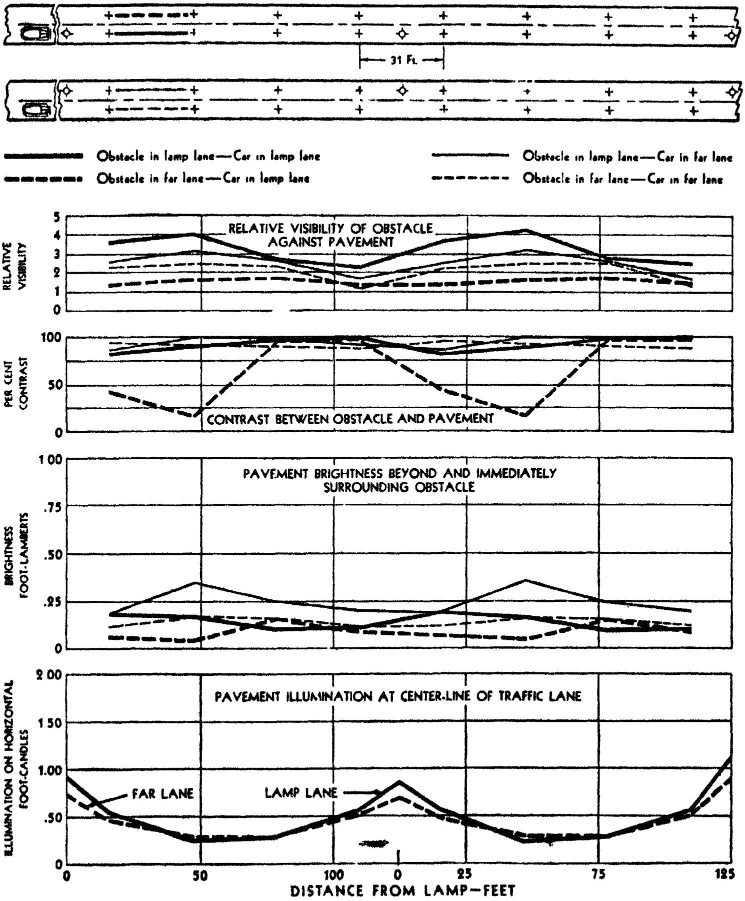

FIG. 13-12.—Measurements taken under incandescent lighting with shielding type of reflector equipment—on Chagrin Boulevard, near Cleveland, Ohio.

duce a 15 per cent increase in visibility with the incandescent installation would require a 45 per cent increase in lamp lumens —from 10,000 to 14,500 lumens.

In making a comparison between the two incandescent installations, on the Balltown Road and on Chagrin Boulevard, it must be kept in mind that factors are involved other than the differences in light distribution. The average obstacle visibility under the Chagrin installation was found to be 2.31, or 33 per cent greater than that with the Balltown incandescent installation. To provide a 33 per cent increase in visibility with the Balltown installation would require one to approximately double the lamp lumens—from 10,000 to 20,000 lumens. The lumens per running foot of road would accordingly be 2½ times as great as on Chagrin Boulevard.

The greater effectiveness of the Chagrin installation is attributable in considerable measure to the much higher utilization efficiency of the luminaires, to the suppression of glare by the shielding, and to the greater uniformity of pavement brightness. It should be pointed out, however, that in the Balltown installation the luminaires are mounted too low for best effectiveness, the ratio of spacing to mounting height is too great and, as already stated, a staggered arrangement would be more advantageous. Correction of these conditions, while increasing the installation costs and reducing the proportion of light reaching the road, would be expected to produce rather more than a compensating increase in the visibility provided. It is important to note, however, that the Balltown installation has an advantage of nearly 20 per cent in the reflection factor of the pavement.

The margin in visibility for the Chagrin installation over the sodium lighting on the Balltown Road is indicated as 15 per cent. It would require an increase of 45 per cent in the output of the sodium lamps—to 14,500 lumens—to compensate for this differential in seeing. The differences in conditions are as outlined in the preceding paragraph.

But one is interested in more than merely the average relation. From a safety standpoint the incidence of areas of lowest visibility is highly important. Thus under the Balltown incandescent installation the visibility of the obstacle at approximately 30 per cent of the test stations was found to be less than the minimum with the Chagrin installation. With the Balltown sodium installation approximately 20 per cent of the visibility readings were below the minimum on Chagrin Boulevard.

In order to obtain a general idea of the visibility afforded on the highways just discussed as compared with that prevailing on city streets, limited studies were made on two urban thoroughfares—Woodward and Gratiot avenues in Detroit.

These thoroughfares carry heavy traffic and are 90 ft. wide from curb to curb. Both are considered to be unusually well lighted. On Woodward Avenue there is 3.3 lamp lumens per square foot of pavement, in a particularly effective type of equipment but with the handicap of a rather dark pavement. On Gratiot Avenue there is 2.2 lamp lumens per square foot, in fairly effective equipment and with the benefit of a light-colored pavement. On Chagrin Boulevard there is 1.6 lamp lumens per square foot of pavement.

Comparing measurements taken with observer and obstacle along representative driving lanes, the average pavement brightnesses and the average obstacle visibilities on the urban thoroughfares are approximately two-thirds of those on Chagrin Boulevard. On the thoroughfares the obstacle visibilities are lower than would be expected from the relative pavement brightnesses because of the glare from the equipments.

It is the opinion of the investigators that such measurements, by themselves, give an incomplete appraisal of visibility for safety on urban thoroughfares. As the traffic increases, the background at times becomes predominantly a shifting pattern of moving vehicles. Vertical illumination then becomes of increasing importance in the discernment of obstacles.

Street Lighting Code.—The Committee on Street Lighting of the Illuminating Engineering Society has produced a Code of Street Lighting[1] as a guide to those interested in the subject. The recommendations of this code are sponsored by some of the highest authorities on street lighting.

The recommendations are based on the use of equipment of the most effective type in the most effective manner. The recommendations should be understood to be minimum values for street lighting.

Better lighting is entirely justified by the increased safety, effectiveness, and convenience which are enjoyed by those using the streets at night. Many street lighting installations throughout the country exceed the recommendations of the code to the advantage of the public.

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[1] *Trans. Illum. Eng. Soc.*, vol. 30, p. 96, 1935.

Light is being used in an effective manner when the luminaire is placed on brackets extending out beyond the curb. When placed back of the curb the effectiveness is reduced and the next larger size lamps or a closer spacing than mentioned in the specifications will usually be required.

With greater heights a somewhat greater spacing is permissible provided the candle power is increased proportionately.

Where there are shade trees, judicious trimming of the trees is advocated where feasible as an alternate to mounting the lamps lower than recommended.

The minimum recommendations of the code are intended to apply to usual and representative conditions. More light should be provided in each classification of lighting:

1. As traffic density increases.
2. When headlight laws restricting beams are not enforced.
3. Where the number of pedestrians is unusually large.
4. Where there are surface-car lines and according to the frequency of car service.
5. Where safety zones are provided if the safety zones are not lighted.

Slightly less light may be supplied:

1. Where there is only one-way traffic.
2. Where parking of automobiles is not permitted.

For light-traffic thoroughfares (not more than 500 vehicles per hour) the minimum recommended is a staggered arrangement of lighting units with luminaires located on brackets extending out beyond the curb at a mounting height of not less than 18 ft.; with this mounting height the spacing should not be greater than 150 ft.; with such mounting height and spacing the lamp rating should not be less than 4,000 lumens. On narrow thoroughfares, *e.g.*, 25 ft. between curbs, lighting units may be located on one side of the street although better results will be obtained if the units are staggered. The minimum mounting height of 18 ft. should be employed only where trees are present or other conditions make a higher mounting height impracticable. Mounting heights between 20 and 25 ft. are recommended where practicable.

For medium-traffic thoroughfares (800 to 1,200 vehicles per hour) the minimum recommended is a staggered arrangement of lighting units with luminaires located on brackets extending out beyond the curb at a mounting height of not less than 18 ft.; with this mounting height the spacing should not be greater than 150 ft.; with this mounting height and spacing the lamp rating should not be less than 10,000 lumens. The minimum mounting height of 18 ft. should be adopted only where trees are present or other conditions make a higher mounting height impracticable. Mounting heights of 20 to 30 ft. are recommended. For lamps of 10,000 lumens or more, mounting heights higher than 18 ft. become particularly important and should be adopted where practicable.

For heavy-traffic thoroughfares (more than 1,500 vehicles per hour) the minimum recommended is an opposite arrangement, or equivalent, of lighting units with luminaires located on brackets extending out beyond the curb at a mounting height of not less than 18 ft., even where trees are present; with this mounting height the spacing should not be greater than 150 ft. on each side of the street; with such mounting height and spacing the lamp rating should not be less than 10,000 lumens. Where trees do not interfere, mounting heights of 20 to 30 ft. are recommended. With lamps of 10,000 lumens or more, mounting heights higher than 18 ft. are particularly important and should be adopted where practicable.

Business streets should be classified as to vehicular traffic in a manner similar to that adopted for thoroughfares and the same minimum standards of illumination should apply for each class, due consideration being given to other local conditions. Retail-business streets should never be lighted to a lower standard than that for medium traffic thoroughfares. Where there is considerable pedestrian traffic these minimum values should be increased. If the luminaires are not placed over the roadway lamp sizes should be increased.

For a given size of lamp the minimum mounting height for both upright and pendent units of the conventional types should be as follows:

	Not Less Than
For lamps of 25,000 lumens and over	**24 ft.**
For lamps of 15,000 lumens	**20 ft.**
For lamps of 10,000 lumens and less	**18 ft.**

For residence streets (nonthoroughfare) the minimum recommended is an 18-ft mounting height for luminaires located on brackets extending beyond the curb, even where trees are present; with this mounting height the spacing should not be greater than 150 ft , although conditions may sometimes necessitate spacings as great as 200 ft.; with such mounting height and spacing the lamp rating should not be less than 2,500 lumens At closer spacings a lower mounting height, not less than 15 ft., is permis-

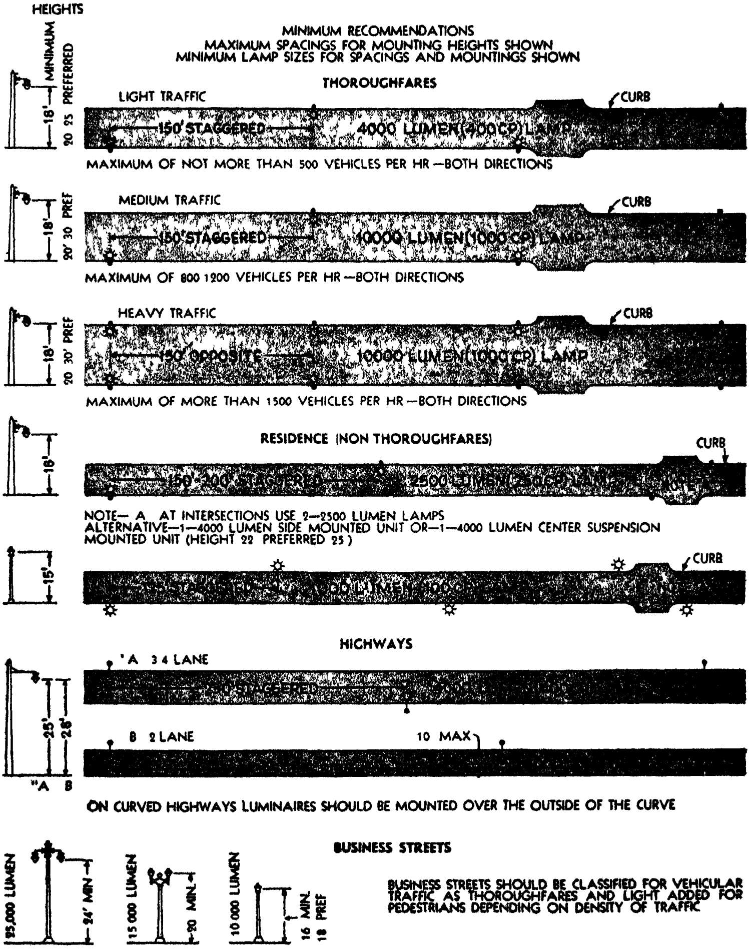
HEIGHTS
MINIMUM
20 25 PREFERRED
18'
MINIMUM RECOMMENDATIONS
MAXIMUM SPACINGS FOR MOUNTING HEIGHTS SHOWN
MINIMUM LAMP SIZES FOR SPACINGS AND MOUNTINGS SHOWN
THOROUGHFARES
LIGHT TRAFFIC
CURB
150' STAGGERED
4000 LUMEN(400CP) LAMP
MAXIMUM OF NOT MORE THAN 500 VEHICLES PER HR—BOTH DIRECTIONS
18'
20' 30 PREF
MEDIUM TRAFFIC
CURB
150' STAGGERED
10000 LUMEN(1000 CP) LAMP
MAXIMUM OF 800 1200 VEHICLES PER HR—BOTH DIRECTIONS
18'
20 30' PREF
HEAVY TRAFFIC
CURB
150' OPPOSITE
10000 LUMEN(1000 CP) LAMP
MAXIMUM OF MORE THAN 1500 VEHICLES PER HR—BOTH DIRECTIONS
18'
RESIDENCE (NON THOROUGHFARES)
CURB
150'-200' STAGGERED
2500 LUMEN(250 CP) LAMP
NOTE
NOTE— A AT INTERSECTIONS USE 2—2500 LUMEN LAMPS
ALTERNATIVE—1—4000 LUMEN SIDE MOUNTED UNIT OR—1—4000 LUMEN CENTER SUSPENSION
MOUNTED UNIT (HEIGHT 22 PREFERRED 25)
15'
CURB
STAGGERED
1000 LUMEN (100 CP)
HIGHWAYS
A 3 4 LANE
250' STAGGERED
B 2 LANE
10 MAX
25'
26'
A
B
ON CURVED HIGHWAYS LUMINAIRES SHOULD BE MOUNTED OVER THE OUTSIDE OF THE CURVE
BUSINESS STREETS
25,000 LUMEN
24' MIN
15 000 LUMEN
20 MIN
10 000 LUMEN
16 MIN
18 PREF
BUSINESS STREETS SHOULD BE CLASSIFIED FOR VEHICULAR TRAFFIC AS THOROUGHFARES AND LIGHT ADDED FOR PEDESTRIANS DEPENDING ON DENSITY OF TRAFFIC

Fig 13-13 —A graphical summary of the street lighting code

sible. Also 1,000-lumen lamps may be used at the minimum mounting height of 15 ft. with closer spacings, preferably not exceeding 125 ft.

Where luminaires are used on center suspension, the mounting height should be not less than 22 ft. and preferably not less than 25 ft.

At intersections of residence streets carrying only local traffic, not less than one 4,000-lumen or two 2,500-lumen lamps should be installed.

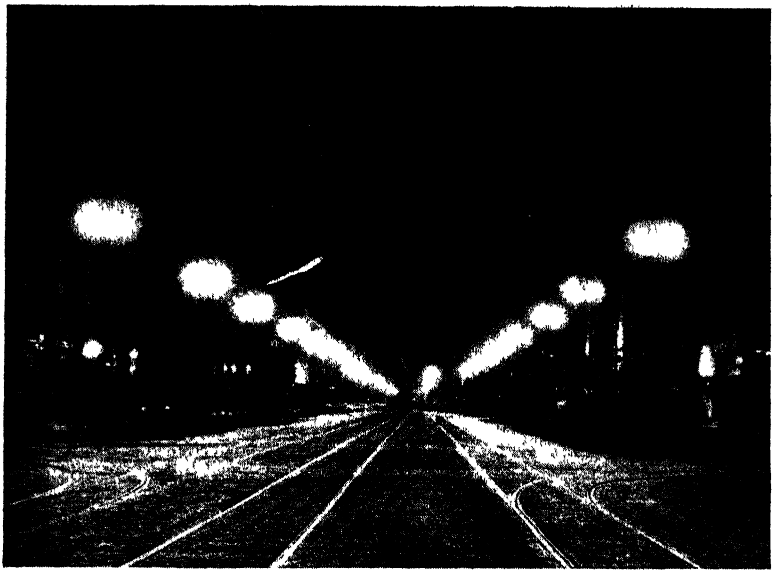

Fig. 13-14.—State Street, Chicago, Ill. Illustrating business-street lighting. G. E. Novalux units.

A graphical summary of the I.E.S. Code is shown in Fig. 13-13.

Examples of high-intensity street illumination in Chicago and Detroit are shown on the following pages and indicate the tendency of the times.

Chicago.—In 1926, 3,150 ft. of State Street was lighted to a new high intensity of 2,000 lumens per linear foot of street. There were 70 standards each supporting two 2,000-watt lamps in rippled-glass globes mounted about 30 ft. above the street. The standards were arranged on opposite sides of the street,

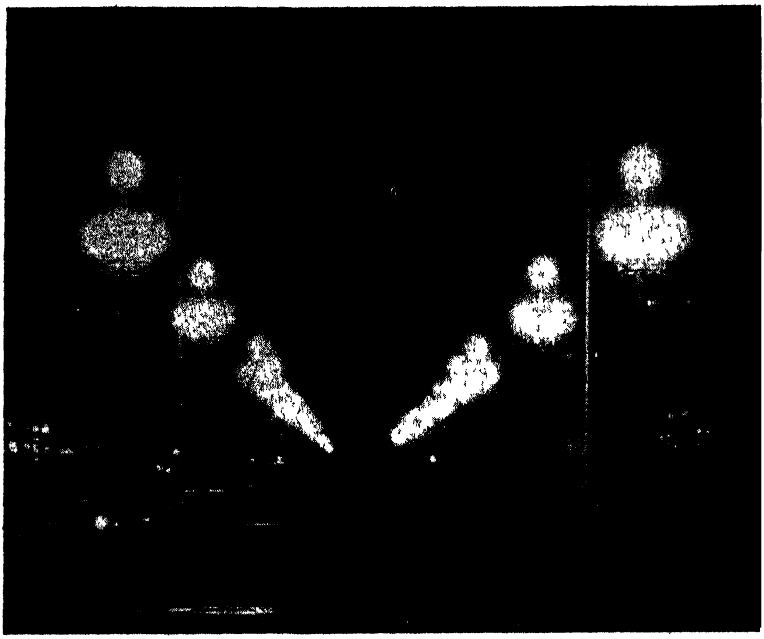

FIG. 13-15.—Washington Boulevard, Detroit, Mich. G. E. Novalux ornamental units

FIG. 13-16.—Outer Drive, Detroit, Mich. Illustrating park driveway lighting G. E. Novalux units.

about 100 ft. apart and opposite each other, as shown in Fig. 13-14.

These lamps operated from a 110–220-volt three-wire direct-current circuit. The system is remotely controlled from a central point by a number of magnetic contactors usually one contactor at each pole.

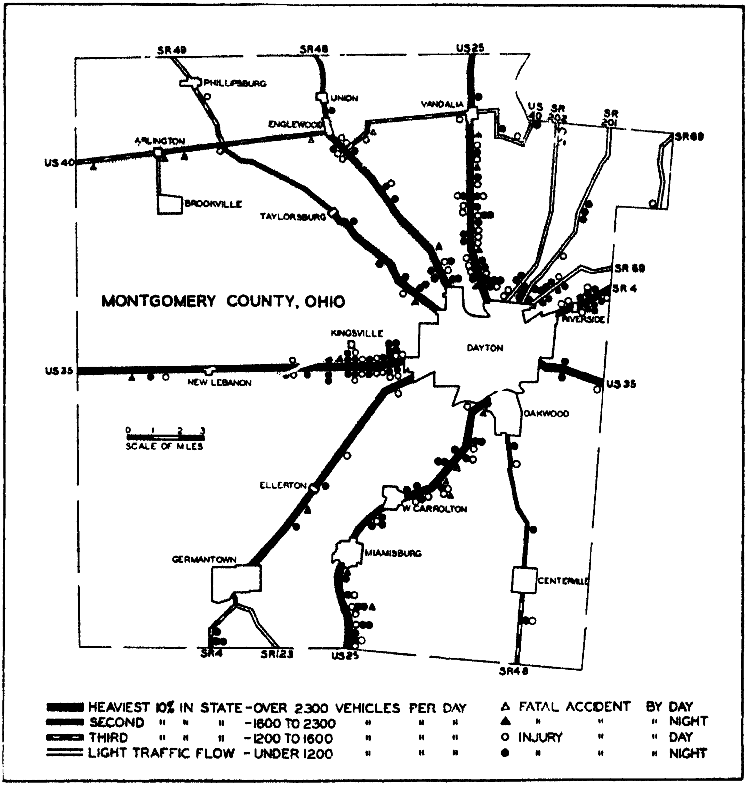

FIG. 13-17.—Accidents in Montgomery County, Ohio, in 18 months of 1934 and 1935.

Detroit.—In 1928 Washington Boulevard in Detroit, with its five-light ornamental illumination system, was said to be the best lighted street in the world. Each standard, of ornamental design, carried five specially designed units each equipped with a 1,000-watt lamp. The arrangement of the units on the pole and the appearance of the installation are shown in Fig. 13-15.

The standards were 32 ft. in height. The globes were designed to refract the upward light into or below the horizontal. The illumination was approximately 2,000 lumens per linear foot of street frontage. All five lamps on each standard operate until one o'clock, while the uppermost lamp remains in service until morning.

TABLE 13-1.—ACCIDENTS AND FATALITIES ON 30 MILES OF HIGHWAY IN MONTGOMERY COUNTY, OHIO

Route No.	Location	Miles	Day accidents		Night accidents	
			Injuries	Fatalities	Injuries	Fatalities
4	County line, ½ mile north....	½	..	..	3	
4	Near Ellerton...............	2	..	..	2	1
4	Riverside to county line......	1½	3	..	7	
25	County line to Miamisburg ...	3½	6	..	8	2
25	Miamisburg to West Carrolton.	1½	1	..	3	
25	West Carrolton to Dayton....	5½	7	1	10	3
25	Dayton to Vandalia..........	7	16	..	17	4
35	Dayton, past Kingsville.......	3	11	..	18	1
48	Dayton, 1½ mile northwest...	1½	2	..	5	1
49	Dayton, 1½ mile northwest...	1½	1	..	3	1
69	Dayton, 1½ mile northeast...	1½	2	..	5	1
201	Dayton, ½ mile north........	½	..	..	4	
201	4 miles north of Dayton......	½				
	Totals....................	30	49	1	85	14

On some of the other important streets standards carrying two 2,000-watt incandescent lamps each were placed 100 ft. apart along each side of the street and opposite each other. The lamps were 26.5 ft. above the curb.

An example of park driveway lighting is shown in Fig. 13-16.

Highway Accident and Lighting Study.—A record of traffic flow and accident locations is desirable in substantiating the need for improved street or highway lighting. Accompanying illustration and data[1] from the Ohio department of highways are instructive. The number of day and night accidents and their location are shown for the highways around Dayton, Montgomery County,

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[1] *General Electric Company Bull.*, LS-1017, December, 1935.

Ohio. The data cover the period from Jan. 1, 1934, to July 1, 1935—18 months. The density of traffic flow is also indicated. The detailed data cover only 30 miles of highway around Dayton. A summary of accident data for Montgomery and Morrow counties, the latter of the rural type, may be seen in Table 13-2.

Table 13-2.—Summary of Traffic and Accident Data, Montgomery and Morrow Counties, Jan. 1, 1934, to July 1, 1935*

Approximate proportion of total traffic:	
By night	¼
By day	¾
Ratio of night to day traffic	⅓
Total state highway mileage	218
Proportion of all night accidents on less than one-fifth (41 miles) of total mileage	¾
Fatal and injury accidents on most dangerous 41 miles:	
Night accidents	128
Day accidents	63
Ratio of night to day accidents	2.03
Ratio of night to day accidents per vehicle-mile	6.1
Ratio of night to day fatal accidents per vehicle-mile	10+
Fatal and injury accidents on remaining 177 miles:	
Night accidents	49
Day accidents	80
Ratio of night to day accidents	0.62
Ratio of night to day accidents per vehicle-mile	1.85
Ratio of night to day fatal accidents per vehicle-mile	3
Estimated annual saving by lighting 41 miles:	
(Half the present night accidents)	
Fatal accidents preventable	8
Personal injury accidents preventable	55
Property damage accidents preventable	200
Estimated cost of lighting 41 miles:	
Proportion of present economic loss from preventable night accidents	⅓

* This and similar analyses indicate that there are in the United States approximately 50,000 miles of highway on which the night accident rate is at least six times the day accident rate and on which corresponding savings can be made by the installation of modern safety lighting.

Street Lighting Systems.—On the following pages are shown some of the street lighting equipment and distribution systems used in street and highway lighting practice. The gas-filled tungsten lamp and the sodium-vapor lamps appear to be the prevailing sources of light although the mercury-vapor lamp has

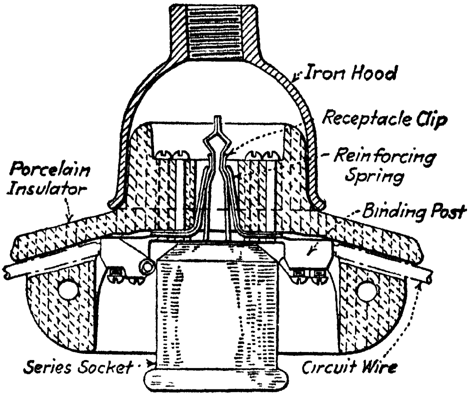

FIG. 13-18.—Cross section of hood and insulator for series bracket showing external wiring.

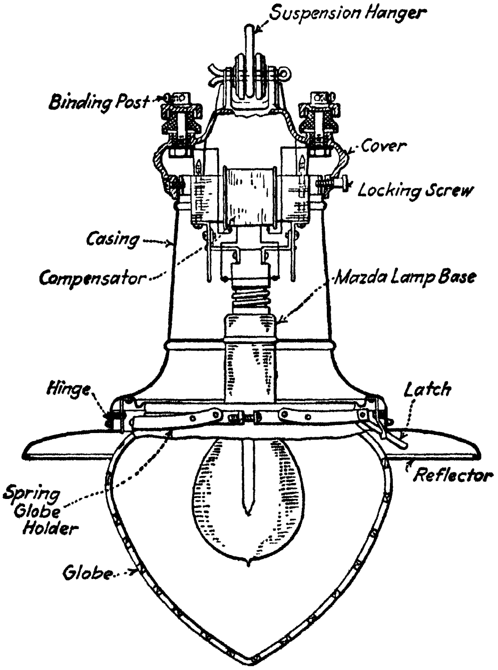

FIG. 13-19.—Construction of the pendent lighting unit for type C lamps.

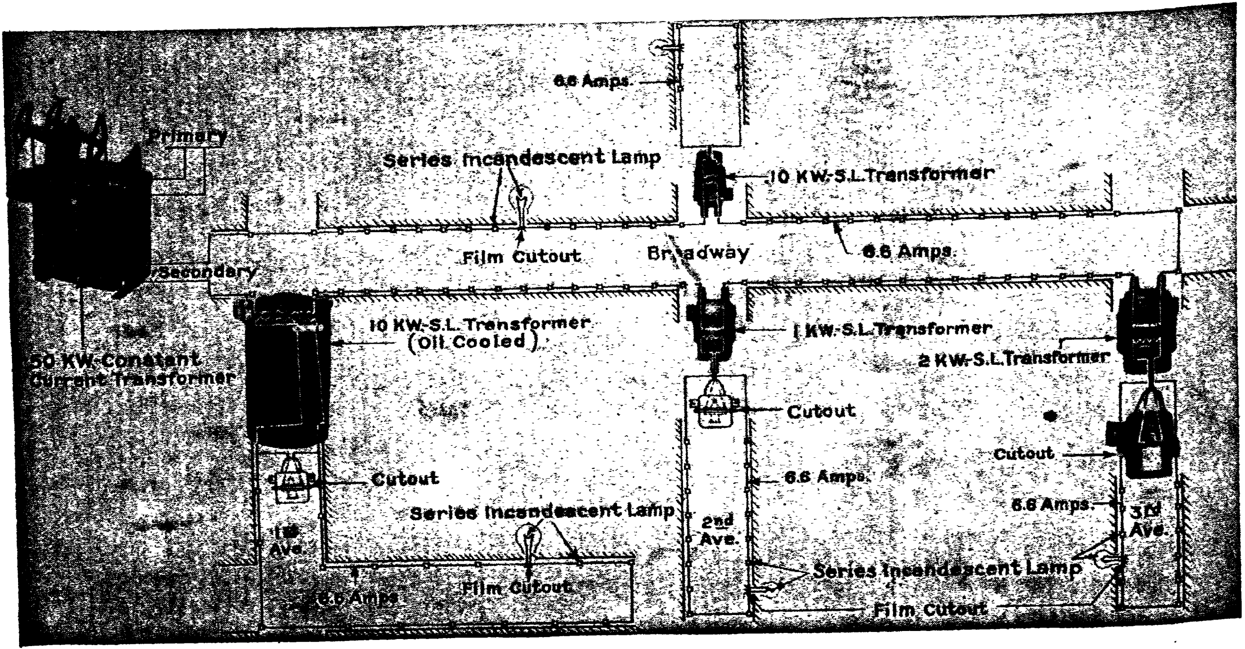

FIG. 13-20.—Diagram showing low-voltage series circuits by series transformers.

possibilities for street lighting and, in fact, is used in many installations in Europe.

Incandescent Lamps.—The gas-filled tungsten filament lamp can be equipped with a variety of accessories suitable for all types of outdoor lighting from the rural highway to the ornamental systems in business districts. Various equipments of glassware and reflectors, together with a wide range of candlepower sizes, ensure a flexibility which adapts this lamp to almost every condition to be met in street lighting service.

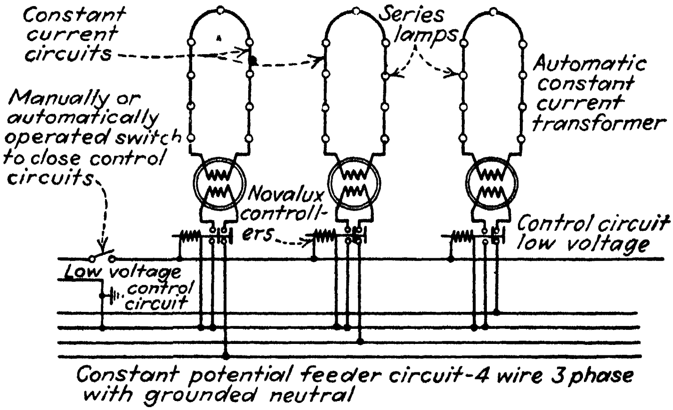
Constant current circuits
Series lamps
Automatic constant current transformer
Manually or automatically operated switch to close control circuits
Novalux controllers
Control circuit low voltage
Low voltage control circuit
Constant potential feeder circuit-4 wire 3 phase with grounded neutral

FIG. 13-21.—Diagram of pilot-wire control. By closing a low-voltage pilot circuit, controllers are operated which connect the transformers to the feeder circuit.

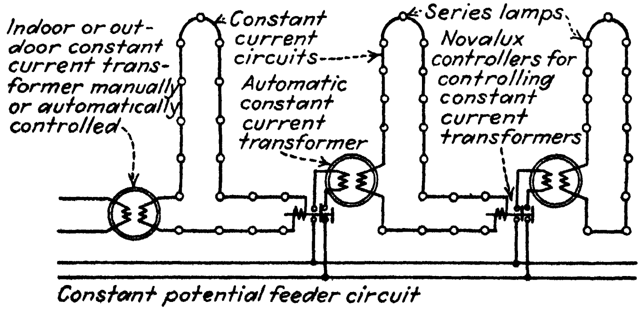
Indoor or outdoor constant current transformer manually or automatically controlled
Constant current circuits
Automatic constant current transformer
Series lamps
Novalux controllers for controlling constant current transformers
Constant potential feeder circuit

FIG. 13-22.—Diagram illustrating cascade control of series lighting circuits Each circuit contains a series controller which controls the one beyond.

The typical construction of the pendant unit is shown in Figs. 13-18 and 13-19. The construction and location of the film cutout together with the receptacle clips and reinforcing springs which short-circuit the socket when the lamp is removed are shown in Fig. 13-18. When 15- or 20-amp. lamps are used on standard series circuits a compensator may be included in the top of the unit (Fig. 13-19).

Series low-voltage transformers are used as shown in Fig. 13-20 to receive energy from a long series circuit and to supply it to a small number of lamps connected in series and located where the high voltage of the ordinary constant-current circuit would be objectionable.

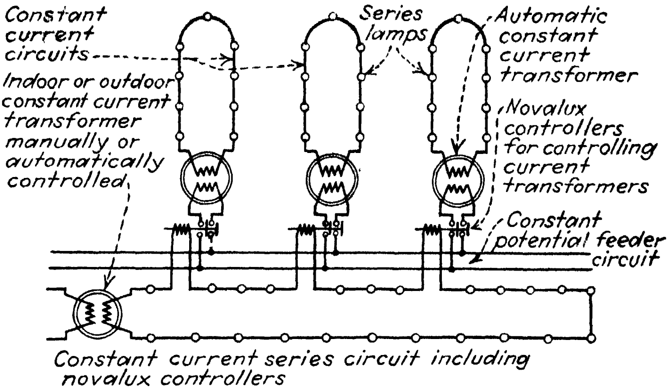
Constant current circuits
Indoor or outdoor constant current transformer manually or automatically controlled
Series lamps
Automatic constant current transformer
Novalux controllers for controlling current transformers
Constant potential feeder circuit
Constant current series circuit including novalux controllers

FIG. 13-23.—Diagram showing series controllers placed in a series lighting circuit which also acts as a control circuit.

Remote control of street lighting circuits may be secured by several methods. In Fig. 13-21 a low-voltage pilot wire operates relays to open or close the transformer circuits. The cascade control is illustrated in Fig. 13-22, while a number of series controllers connected in one series lighting circuit operate other series circuits as may be seen in Fig. 13-23. Still another is the carrier-current control wherein a high-frequency circuit is coupled through a capacitor to the power line and a tuned relay at the substation receives the high-frequency energy and operates the switch of the lighting circuit.

Data on standard incandescent type C lamps for street lighting service are given in Table 13-3. The lamps are fitted with mogul screw base.

TABLE 13-3.—INCANDESCENT TYPE C LAMPS FOR STREET LIGHTING SERVICE

Amperes	Lumens	Average volts
6.6	1,000	9.8
6.6	2,500	22.2
6.6	4,000	33.9
6.6	6,000	51.1
15	4,000	14.2
20	6,000	15.3
20	10,000	25 0
20	15,000	37.9
20	25,000	60.7

The 15- and 20-amp. lamps are designed for the base-up burning position. Lamps for the base-down burning position are also available. The 25,000-lumen lamp is not recommended for base-down burning.

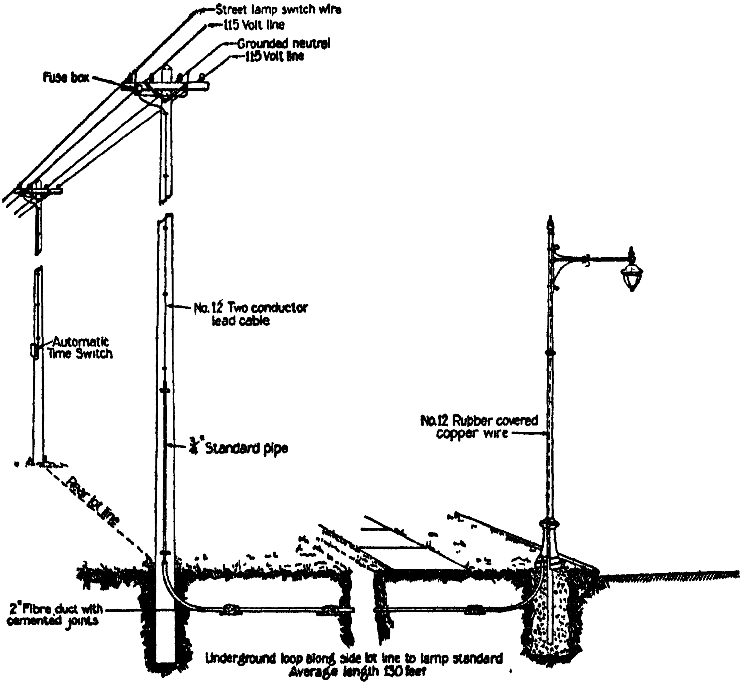
Street lamp switch wire
115 Volt line
Grounded neutrel
115 Volt line
Fuse box
Automatic Time Switch
No. 12 Two conductor lead cable
¾" Standard pipe
No.12 Rubber covered copper wire
Rear lot line
2" Fibre duct with cemented joints
Underground loop along side lot line to lamp standard
Average length 130 feet

FIG. 13-24.—Pole line placed along rear lot line in residential section.

In residential districts the pole lines are often located along the rear lot lines to improve the appearance of the streets. The wires then enter the houses from the rear and the street lamps are served by underground lines running to the lamp poles beside the street. This practice is illustrated in Fig. 13-24.

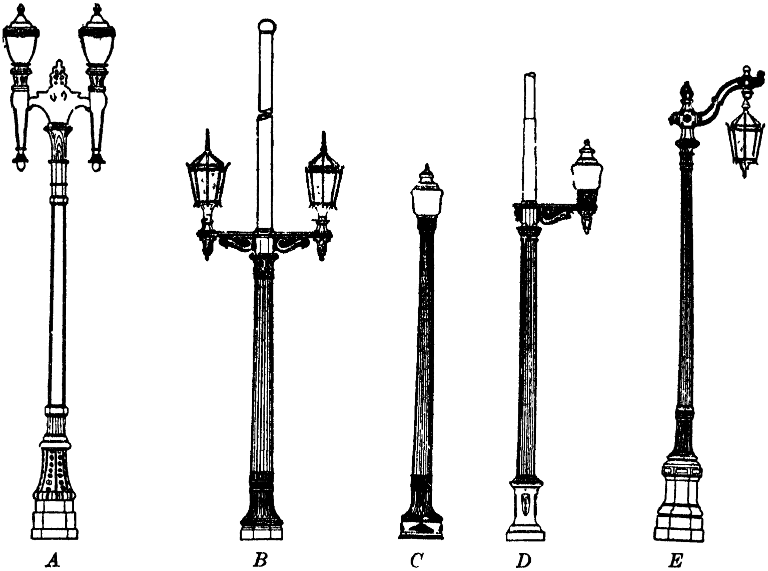

FIG. 13-25.—Methods of mounting White Way luminaires. *A*, specially designed ornamental two-light standard with Novalux form 12 ornamental luminaire. *B*, trolley-pole twin-bracket type with Novalux form 18 ornamental lantern-type luminaire. *C*, ornamental standard for single light with form 9 Novalux luminaire. *D*, single-light ornamental bracket for trolley-pole mounting with Novalux form 9 luminaire. *E*, ornamental mast-arm mounting with Novalux form 19 ornamental lantern-type luminaire.

Some of the types of lighting standards and luminaires are shown in Fig. 13-25. Others have more lamps, even as many as five, as in Fig. 13-15.

The sodium-vapor lamp due to its high efficiency and because of its color, has found its principal field of application in highway lighting. The lamp necessitated a new design of luminaire for use in its application and two have been developed. One is the "airplane-type" sodium luminaire (General Electric Company) consisting of both parabolic and plane reflecting surfaces to give a characteristic unsymmetrical light distribution desirable for highway lighting service. The construction of this unit is indicated in Fig. 13-26.

The other is the "butterfly sodium luminaire" (Westinghouse Electric & Manufacturing Company) and consists of a cast aluminum upper housing to which specially shaped alzak sheet-aluminum reflectors are attached. Four of these reflectors are approximately vertical and two approximately horizontal, thereby projecting the beams of light in opposite directions along the highway with very little light emitted toward areas to the sides of the highway.

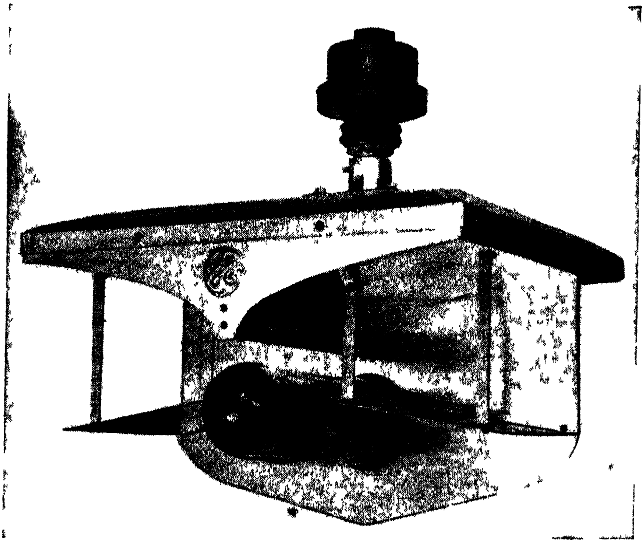

FIG 13-26 —The "airplane type" of sodium luminaire.

These two luminaires give excellent lighting results especially in those applications where vehicular traffic is a problem and high-intensity illumination necessary.

Observations and tests indicate a desirable mounting height of 30 ft.[1] and a spacing not more than 240 ft., and less for the 4,000 lumen lamp. A mounting height to spacing of 1 to not more than 6 ft. appears desirable.

The High-intensity Mercury-vapor Lamp.—While the widest application of the high-intensity mercury lamp in this country has been in industrial illumination, in England very extensive use has been made of this lamp for the lighting of streets and highways. Bourne states,[1]

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[1] CLEAVER, *Trans. Illum. Eng. Soc.*, vol. 30, p. 703, 1935.

> The usual type of highway lighting installation in England employs a number of 400-watt, high-intensity lamps, giving 16,000 lumens each, at a spacing of 125 to 160 ft., with a mounting height from 22 to 28 ft. The level of illumination obtained on the road is thus rather higher than the usual intensity found in this country. It is usual for drivers of automobiles to switch off their headlights when entering such a section of road. They can see very easily on such a lighted section and headlights are really of no value. Luminaires are of such construction that glare is minimized and they give the required light distribution on the road surface.
>
> In many installations the lamps are operated horizontally, control of the arc being obtained by a magnet system. In this case luminaires somewhat similar to the sodium lamp luminaires of the "airplane" type have been employed. Increased efficiency in control of light distribution has been obtained in this way.
>
> The mercury lamp installations in England are invariably operated on a multiple circuit, a reactor being connected in series with the line, the voltage of which is between 210 and 250 volts. . . .
>
> The use of these lamps for lighting roads in business, residential, and rural districts is becoming widespread. Installation of these lamps may be seen in almost any town of importance throughout the country.
>
> In addition to the 400-watt lamp, sizes of 250 and 700 watts have been developed, the former for lighting less important streets and the latter for lighting large open areas. . . .
>
> It should be remembered in this connection that in all lighting installations in England the lamps are connected in multiple and the line voltage is about twice the value common in this country.

The high-intensity mercury-vapor lamp and an incandescent lamp have been combined in a luminaire for street lighting service in this country. The unit may consist of a 400-watt high-intensity mercury lamp burned base down and a 200-watt tungsten incandescent lamp burning base up directly over the mercury lamp. The efficiency of the combination is only about 29 lumens per watt against 35 lumens per watt for the mercury lamp alone but the incandescent lamp provides heat to ensure the starting of the mercury lamp in cold weather, improves the color of the light, and supplies some light in the event that the mercury lamp does not restart promptly after a power interruption.

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[1] Bourne, *Trans. Illum. Eng. Soc.*, vol. 30, p. 722, 1936.

These luminaires may operate from a 115 to 230-volt three-wire service, in which case the mercury lamp operates from the 220-volt and the incandescent lamp from the 110-volt line. The reactor and capacitor for the mercury lamp are mounted within the luminaire. The business section of Grand Island, Neb., was lighted by 160 of these units in ornamental luminaires in 1936.

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CHAPTER XIV

LIGHTING THE HIGHWAYS AND AIRWAYS

HIGHWAYS

The tremendous growth of motor-vehicle traffic has occasioned extensions and improvements in highway construction. These have encouraged vehicular traffic resulting in greater traffic density and in higher speed. Highways differ from urban streets in that there are fewer pedestrians, fewer crossings, and generally fewer obstructions to vision. They carry less local and more long-distance traffic Hence few motorists resist the temptation to drive at relatively high speeds on open highways.

Highway Lighting.—The automobile headlight is not a satisfactory solution of highway lighting. Although much progress in headlight design and lamp construction has been made during recent years, the beam from the best headlight, adjusted to comply with the law, is barely sufficient to detect an obstruction or a darkly dressed person against a dark background at a safe distance in front of a fast driven vehicle. Considering the number of cars that are operated with inferior, defective, or improperly adjusted headlights together with the decreased range of the headlight beam at times due to uneven terrain and the sharp cutoffs of the beam, other lighting is necessary for safety on our highways at night. Even small units considerable distances apart may serve as markers for the highway.

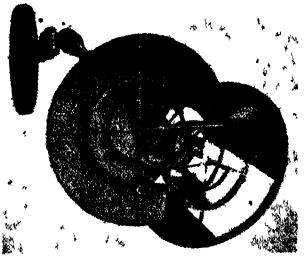


FIG. 14-1.—Highway-lighting unit, showing the nest of parabolic reflectors on the near side and the flexible method of mounting the unit.

Because of the mileage of our highways the lighting unit must be efficient, effective, durable, and of low first cost. One of the first units of this type is shown in Fig. 14-1 and its principle is illustrated in Figs. 14-2, and 14-3. While this type has been superseded by units equipped with refractors the principles involved in lighting the road surface are instructive. This unit consists of six fire-enameled steel parabolic reflectors of three sizes, each set of three having a common axis and common focus and located on opposite sides of the lamp (see Fig. 14-1). The closed ends of the reflectors are removed and a rectangular opening is cut in the lower part of them. With this arrangement much of the light is redirected along the road. Very little goes to the sides or in an upward direction. Furthermore the narrow,

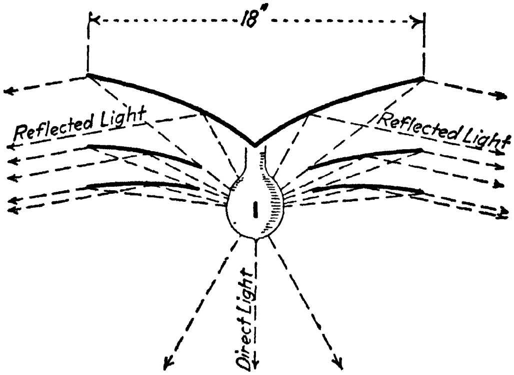


Fig. 14-2.—Diagram showing the paths of the reflected light and direct light from Novalux highway lighting unit.

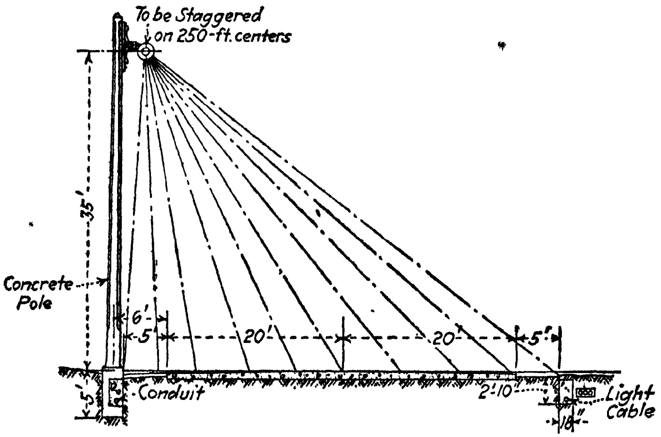


Fig. 14-3.—Typical section across Lincoln Highway.

intense beam of light will illuminate the road for a great distance in both directions. This unit makes economically possible the satisfactory lighting of highways which must otherwise remain unlighted, or at least insufficiently lighted.

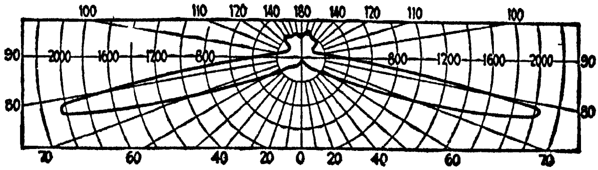


FIG. 14-4.—Candle-power distribution showing greatest intensity in a plane about 22½ deg. from curb line.

The fixture has an adjustable bracket, so that the rectangular openings may be turned toward the road surface and the unit

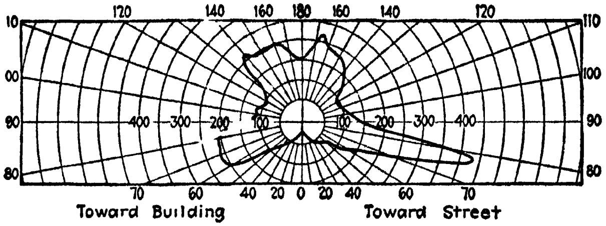


FIG. 14-5.—Candle-power distribution in a vertical plane at right angles to curb line indicating the low intensity toward residences.

tipped when installed on hills or at curves. This unit should be mounted 30 to 35 ft. above the road surface.

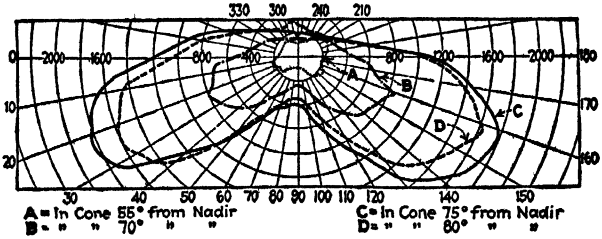


FIG. 14-6.—Laboratory tests of lateral candle-power distribution in cones varying from 50 deg. to 80 deg. from the nadir.

Later refractors were used in highway lighting luminaires to increase the percentage of light directed to the roadway. The unit presents a more pleasing appearance and shows less depreciation from dirt. These refractors consist of two elements with horizontal prisms on the outer surface of the inner one to distribute the light as desired in vertical angles and vertical prisms on the inner surface of the outer element to direct the light along the road, taking it from the sides of the road where it is not needed. The two elements are then sealed to eliminate dirt, etc., and only the perfectly smooth surfaces are exposed.

The distribution of light in different directions and the illumination produced by refractors of this class are shown in Figs. 14-4 to 14-7.

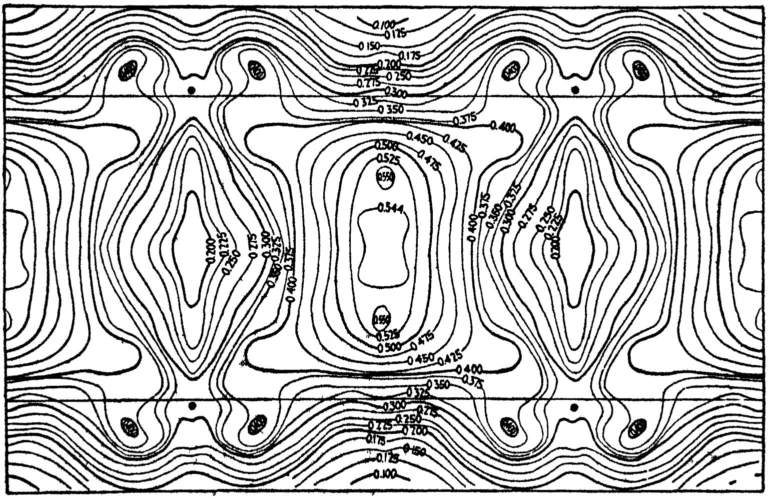
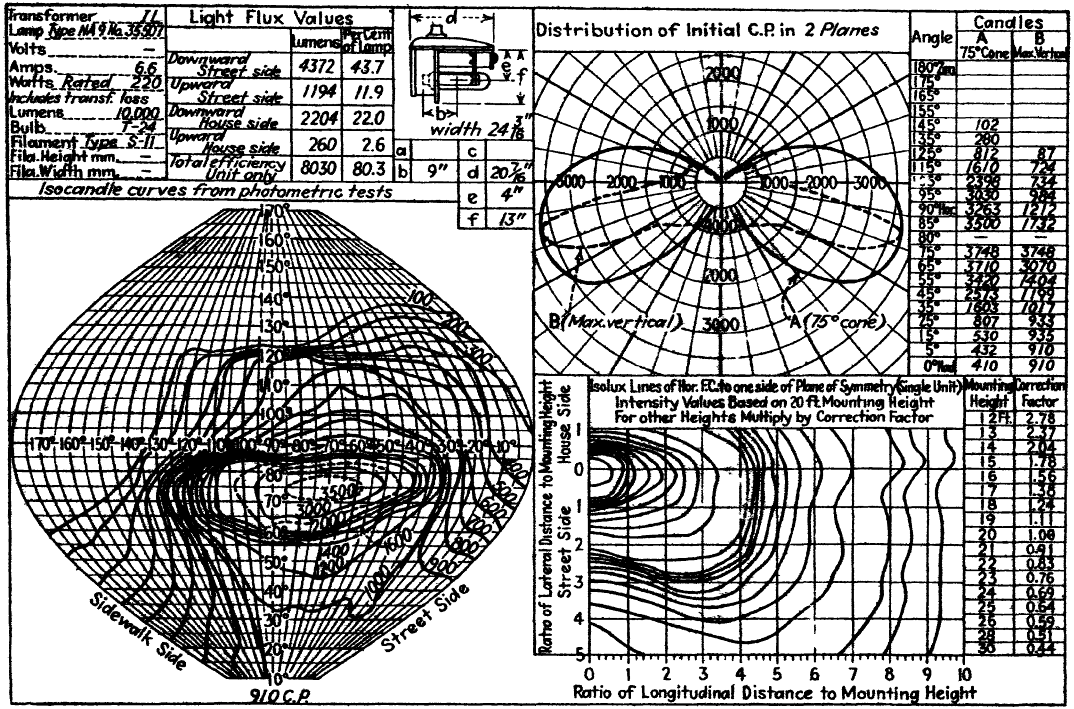


FIG. 14-7.—Isolux curves with "bi-lux" refractor, producing asymmetric distribution with 6,000-lumen lamps mounted on 14-ft. posts 100 ft. apart.

The distribution of light from a General Electric "airplane type" sodium luminaire with a 10,000-lumen lamp is shown by the isocandle curves of Fig. 14-8. This illustration shows, perhaps better than polar curves, the effect of a reflector or a refractor in distributing the light from the lamp.

The requirements for distribution of light up and down a narrow strip of highway with but little light distributed elsewhere lead naturally to designs of luminaires that are likely to occasion serious glare, which militates against the very effectiveness of lighting that is sought. One ready means of reducing such glare is to mount the luminaire high. Notwithstanding the increased costs which this entails, a relatively high mounting height must



Transformer IL
Lamp Type NA 9 No. 35507
Volts —
Amps. 6.6
Watts Rated 220
Includes transf. loss
Lumens 10,000
Bulb T-24
Filament Type S-11
Fila. Height mm. —
Fila. Width mm. —

Light Flux Values	Lumens	Per Cent of Lamp
Downward Street side	4372	43.7
Upward Street side	1194	11.9
Downward House side	2204	22.0
Upward House side	260	2.6
Total efficiency Unit only	8030	80.3

width $24\frac{3}{16}''$

a		c	
b	9"	d	$20\frac{7}{16}''$
		e	4"
		f	13"

Isocandle curves from photometric tests

Angle	Candles A 75° Cone	Candles B Max. Vertical
180° Zen.		
175°		
165°		
155°		
145°	102	
135°	280	
125°	812	87
115°	1610	724
105°	2398	734
95°	3030	984
90° Hor.	3263	1212
85°	3500	1732
80°	—	—
75°	3748	3748
65°	3710	3070
55°	3420	1404
45°	2573	1199
35°	1603	1017
25°	807	933
15°	530	935
5°	432	910
0° Nad.	410	910

Mounting Height	Correction Factor
12 Ft.	2.78
13	2.37
14	2.04
15	1.78
16	1.56
17	1.38
18	1.24
19	1.11
20	1.08
21	0.91
22	0.83
23	0.76
24	0.69
25	0.64
26	0.59
28	0.51
30	0.44

Isolux Lines of Hor. F.C. to one side of Plane of Symmetry (Single Unit) Intensity Values Based on 20 ft. Mounting Height For other Heights Multiply by Correction Factor

FIG. 14-8.—Isocandle curves and data for the "airplane type" sodium luminaire.

be advocated in highway lighting with the luminaires usually designed for this purpose. They should be mounted on long bracket arms so as to extend out over the roadway. This position will produce a continuous specular surface reflection upon the roadway, which will greatly increase visibility by the silhouette method.

One of the results of the researches by Reid and Chanon discussed in the preceding chapter has been the development of the high-visibility type of luminaire. This unit produces a cutoff of light rays at an angle that will minimize glare in the direction of the approaching traveler and at the same time produce a distribution of light that will offer substantially uniform brightness on the street as viewed by the traveler. The appearance of the high-visibility system is shown in Figs. 14-10 and 14-12. The reflecting element is of alzak aluminum and the surfaces specially and accurately shaped to give the desired light distribution. The appearance of one of these luminaires is shown in Fig. 14-9.

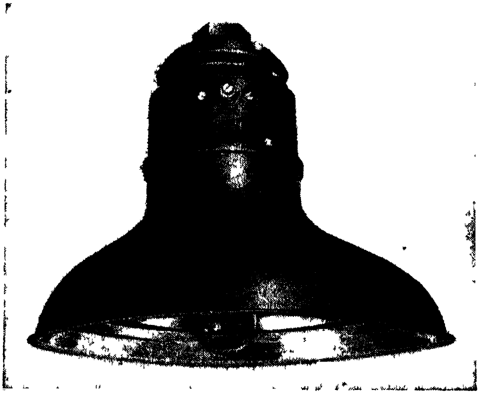


FIG. 14-9.—The high-visibility type of luminaire

The following table from the I.E.S. Highway Lighting Code (1936) sets forth the order of *illumination intensity* that should be produced on highways. In proportion as traffic density or speed upon highways of stated types is relatively great, the higher average intensities of illumination should be sought. Illustrative spacings and sizes of lamps fitting approximately into these recommendations are presented but other combinations of spacing and lamp size to provide the equivalent illumination may be preferable under some circumstances.

TABLE 14-1.—HIGHWAY LIGHTING CODE RECOMMENDATIONS

	Pavement width		
	2 lanes	3 lanes	4 lanes
Pavement permanently light in color, lumens delivered per square foot of pavement surface*	Of the order of 0.2 to 0.5		
Illustrative arrangements*			
Luminaire spacing, ft.	240 to 250	240 to 250	240 to 250
Mounting height, ft.	25 to 30	25 to 30	25 to 30
Lamp lumens	6,000	6,000 to 10,000	6,000 to 10,000
Luminaire spacing, ft.	200	200	200
Mounting height, ft.	25	25	25
Lamp lumens	6,000	5,000 to 10,000	6,000 to 10,000
Luminaire spacing, ft.	125	125	125
Mounting height, ft.	25	25	25
Lamp lumens	4,000	4,000	6,000
Darker pavements, oil polished, lumens delivered per square foot of pavement surface*	Of the order of 0.3 to 1.0		
Dull black pavements, lumens delivered per square foot of pavement surface*	Of the order of 1.0 to 2.0		

* The illumination on the pavement surface which is here recommended may be obtained in a variety of ways, as by larger illuminants spaced more widely or smaller illuminants spaced more closely. Each example of spacings and lamp sizes illustrates one of several possible arrangements. The best selection of arrangements may vary with local circumstances. The illustrations given are based upon the more common pole spacings, but the growing tendency to separate the lighting poles from the rural line will free the lighting design from such restrictions.

Of the total lumens produced under usual conditions, 20 to 50 per cent is delivered upon the highway depending upon the type of equipment employed, the location of the light sources, etc. As large proportions of the light flux are delivered along the highway, glare tends to become more severe unless the utmost skill is exercised in its avoidance. As glare may greatly detract from the effectiveness of the illumination its minimization is at all times of large importance.

No practicable increase in light output of lamps along the side of a highway can compensate for failure to locate the lamp over the highway. These recommendations are based upon the assumption that they will be mounted well out over the highway; on three-lane and wider highways at least two rows of lamps are recommended.

Lamps should be mounted at least 25 ft. above grade. Higher mounting heights usually afford greater lighting effectiveness.

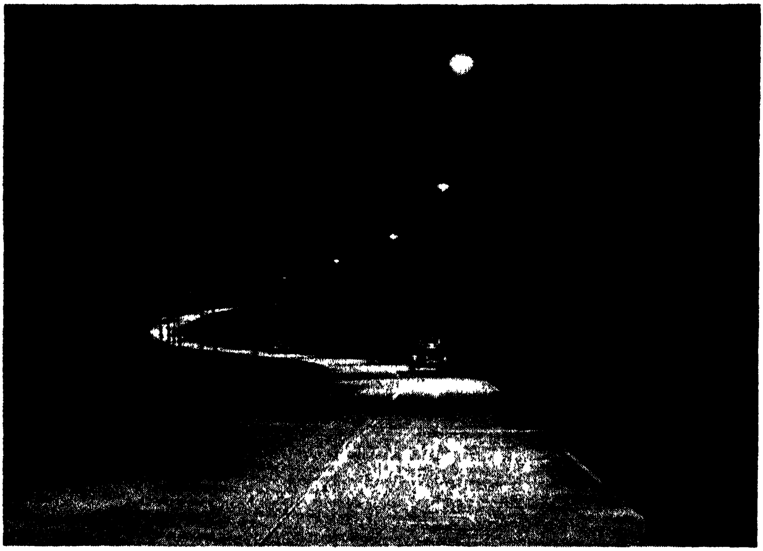


FIG. 14-10.—The high-visibility lighting system on State Route 146, Schenectady, N. Y. Lamps 25 ft. above the street and 125 ft. apart.

On curved highways luminaires should be mounted over the outside of the curve.

A graphical summary of the I.E.S. Code is shown in Fig. 13-13.

Examples of *present highway lighting practice* are described and illustrated on the following pages.

An all-incandescent highway system is shown in Fig. 14-10, and covers 5.6 miles of State Route 146, Schenectady, N. Y.

The lamps are 4,000-lumen series bar-filament lamp in General Electric high-visibility luminaires. The spacing is 125 ft. and mounting height 25 ft. The high-visibility luminaire consists of a special metal reflector which directs much of the light to the road in a manner that produces quite uniform brightness and at the same time suppresses glare by shielding the light source.[1]

The Ohio State Safety Council in its safety educational program is sponsoring as one of its projects the lighting of 48 safety highways. The initial step is the Canton "safety educational highway" shown in Fig. 14-11.[2]

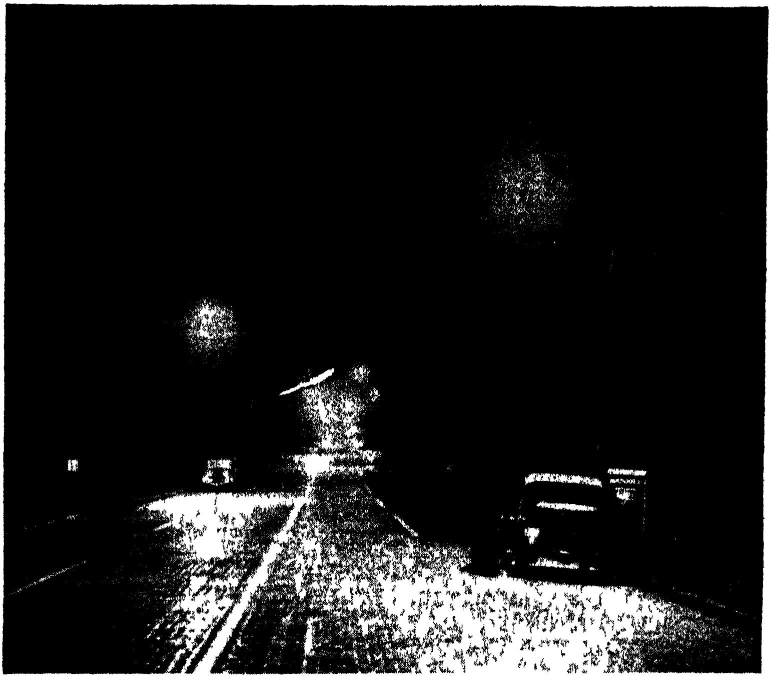


FIG. 14-11.—The "safety highway" on Route 8 in Canton, Ohio. 10,000-lumen sodium lamps, placed 25 ft. above the street and spaced 220 ft.

This 1-mile installation is on Route 8 north of Canton, Ohio. Twenty-five 10,000-lumen General Electric sodium lamps and airplane type luminaires provide an efficient golden-yellow light, well distributed over the broad pavement so that even objects far ahead on the road are easily and quickly seen. These lamps are suspended 25 ft. above and over the roadway and at about 220 ft. spacing.

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[1] *Mag. of Light*, vol. 5, p. 13, December, 1913.

[2] *Mag. of Light*, vol. 5, p. 13, December, 1936.

A unique system of highway safety lighting, employing both sodium units and high-visibility incandescent units, lights the Akron-Cuyahoga Falls, Ohio, highway and is shown in Fig. 14-12.[1] The 4,000-lumen incandescent units are used to light the two-lane roadway at each end of the bridge while 10,000-lumen sodium units illuminate the bridge. Dangerous sections of the highway are illuminated by 6,000-lumen high-visibility lamps.

FIG. 14-12.—The high-visibility incandescent and sodium-vapor combination system between Akron and Cuyahoga Falls, Ohio.

In recommending sodium luminaires for the bridge it was the belief that the golden-yellow color would react on motorists as a warning signal. Observations have fully substantiated this belief. As motorists approach the bridge they slacken their pace.

AUTOMOBILE HEADLIGHTING

The National Safety Council's Vehicle Lighting Code specifies that headlights

> . . . on motor vehicles shall be so arranged that the driver may select at will between distributions of light projected to different elevations. . . . There shall be an uppermost distribution of light, or composite

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[1] *Mag. of Light*, vol. 5, p. 13, December, 1936.

> beam, so aimed and of such intensity as to reveal persons and vehicles at a distance of at least 350 ft. ahead for all conditions of loading. The maximum intensity of this uppermost distribution of light or composite beam 1 deg. of arc or more above the horizontal level of the lamps when the vehicle is not loaded shall not exceed 8,000 apparent candle power, and at no other point of the distribution of light or composite beam shall there be an intensity of more than 75,000 apparent candle power.
>
> There shall be a lowermost distribution of light, or composite beam so aimed that when the vehicle is not loaded, none of the high intensity portion of the light which is directed to the left of the prolongation of the extreme left side of the vehicle shall, at a distance of 25 ft. ahead, project higher than a level of 10 in. below the level of the center of the lamp from which it comes. . . . In no event shall any of the high intensity of such lowermost distribution of light or composite beam project higher than a level of 42 in. above the level on which the vehicle stands at a distance of 75 ft. ahead. . . . All road lighting beams shall be so aimed and of sufficient intensity to reveal a person or vehicle at a distance of at least 100 ft. ahead.

Thus the Code specifies the multiple-beam practice with headlights that provide at least two beams, one aimed high enough to reveal obstacles at a distance of 350 ft., and another aimed to avoid glare, the driver to be responsible for using the proper beam. When the beams are correctly adjusted and used this system incorporates all of the elements needed to satisfy both the driver behind the lights and the other users of the highways.

Automobile Headlamps.—The automobile headlamp consists almost universally of a reflector of parabolic or modified parabolic contour, a 6-volt lamp of one, two, or more filaments and a lens to assist in controlling the light. The two lamps should illuminate the highway for several hundred feet in front of the car and at the same time not produce objectionable glare in the eyes of approaching drivers.

The opinion held by substantially all authorities the world over who have made a study of the characteristics and use of headlight beams in relation to highway safety is that reasonable safety in driving at night now demands at least two beams of different characteristics under the control of the driver—one for driving on the open road and the other for use when meeting other vehicles.

In the multi-filament system two or more sources are included in each lamp to produce more than one beam with the same optical elements. One beam is for driving on the open road and requires a concentration of light through a narrow vertical angle. This is most efficiently accomplished if the light source is at the focal point. For the lower beam, the light must be spread over a somewhat greater vertical angle. The efficient method of producing the tilt of this beam is by placing the second source above the focal point.

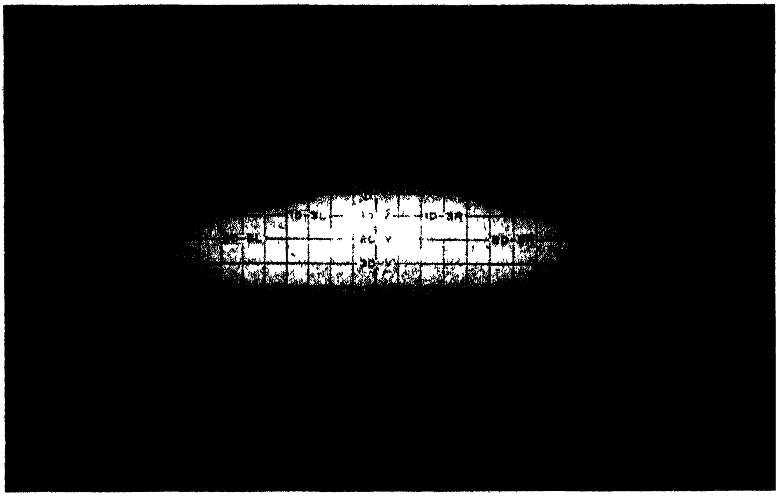

FIG. 14-13.—Pattern of a driving beam, conforming to present-day aiming restrictions, produced with line sources, 5-in. paraboloidal reflectors, and lenses of the general type.

With the proper use of the driving and meeting beams it becomes feasible to design a driving beam with sufficient light above the horizontal to ensure safety and comfort under modern driving conditions. Such a beam would not have the sharp upper gradient.

Nearly all the cars on the road have the dual beam headlamp but no effort, legal or educational, has been made to promote the use of the depression beam on meeting other cars.

A favorable filament form for a 32-candle-power lamp in a reflector of 5-in. diameter and ⅞-in. focal length, was found to be a horizontal helix of 0.03-in. diameter and 0.14-in. length. A unit of this size produced a high-intensity zone of 2 deg. by 6 deg. with a maximum value from one lamp of 20,000 candle power.

The tolerance in positioning of the light source in a 5-in. reflector of ⅞-in. focal length should be limited to about 0.025 in. This tolerance becomes feasible with a lamp having a prefocused base that is seated at three points related definitely to the reflector.

An asymmetric beam for meeting vehicles can be produced by using a lens or reflector contour modification which directs the major portion of the light to one side of the road. Or the sources may be so arranged that the beam is shifted to the right as well as downward. This can be done by rotating the standard two-filament bulb from its usual position so that the second source is to the left as well as above the source of the driving beam. The objection to this method is that there is no depressed beam on both sides for city use.

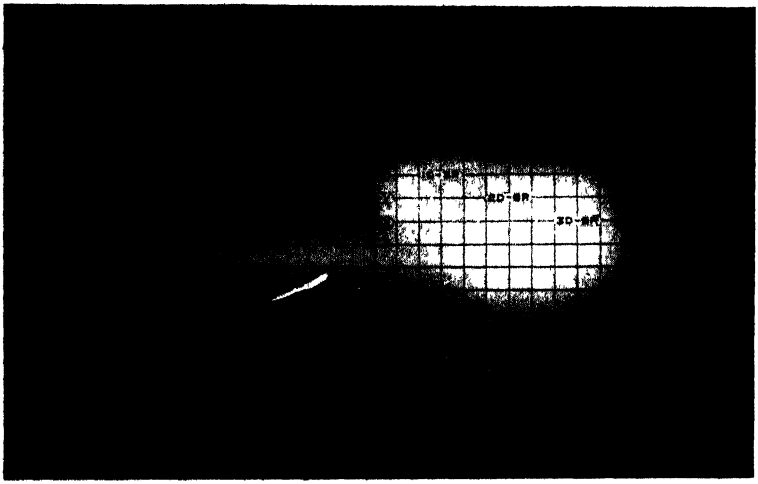

FIG. 14-14.—Pattern of an asymmetric meeting beam produced by 5-in. paraboloidal reflectors and lenses.

A double-bar-filament prefocused headlight lamp appeared on several of the 1936 automobiles. Instead of the conventional V filament this lamp had two horizontal coiled bar filaments located side by side, with one of them, the passing filament, slightly above and to the left of the other. In switching from the lower right-hand filament, which is in focus and furnishes the driving beam, to the upper left-hand filament the beams of both headlamps are shifted to the right and slightly downward, thus throwing an intense beam along the right-hand curb benefiting the driver of the car so equipped as well as the driver of the oncoming car.

Beams of light from lamps of this type may produce patterns similar to those shown in Figs. 14-13 and 14-14.[1]

The candle power of a headlight beam required to reveal objects of different reflection factors is shown in Fig. 14-15.[2] In Fig. 14-16 are shown the stopping distances for various speeds.[3]

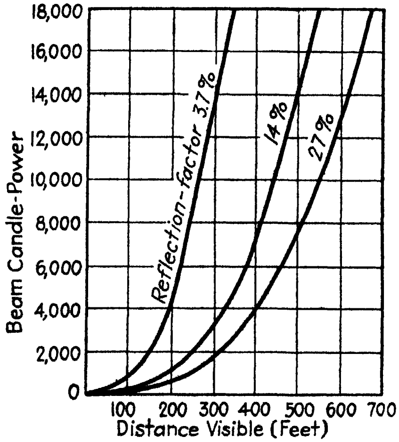

FIG. 14-15.—Candle power of headlight beam required to reveal objects of different reflection factors.

From a study of these data it will be seen that the candle power of the headlight beam should be sufficient to reveal objects at a distance of about 500 ft. at speeds of 50 miles per hour in order to avoid danger of accidents.

AVIATION LIGHTING[4]

In 1926 the Air Commerce Act authorized the Secretary of Commerce, generally, "to establish and maintain intermediate landing fields, lights, signals and radio direction finding apparatus, and other structures and facilities, *excepting airports,* used as aids to navigation."

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[1] *Trans. Illum. Eng. Soc.*, vol. 29, p. 175, 1934.

[2] *General Motors Corporation Bull.*

[3] *Ibid.*

[4] MACKALL, K. W., "Airport Lighting," *Trans. Illum. Eng. Soc.*, vol. 27, p. 123, 1932.

In 1936 there were some 50,000 miles of airways in the United States. Of these approximately 22,000 miles were lighted and equipped with radio beacons, radio communication, and teletypewriter service. There were approximately 1,325 airports and 250 intermediate landing fields.

The airports are, in general, established and maintained by commercial companies or municipalities.

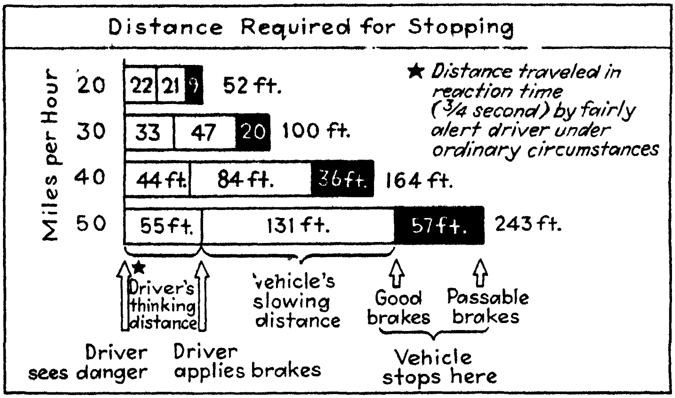


FIG. 14-16.—Distances required for stopping.

The Airport.—The plan of an airport and some of the details are indicated in Fig. 14-17.

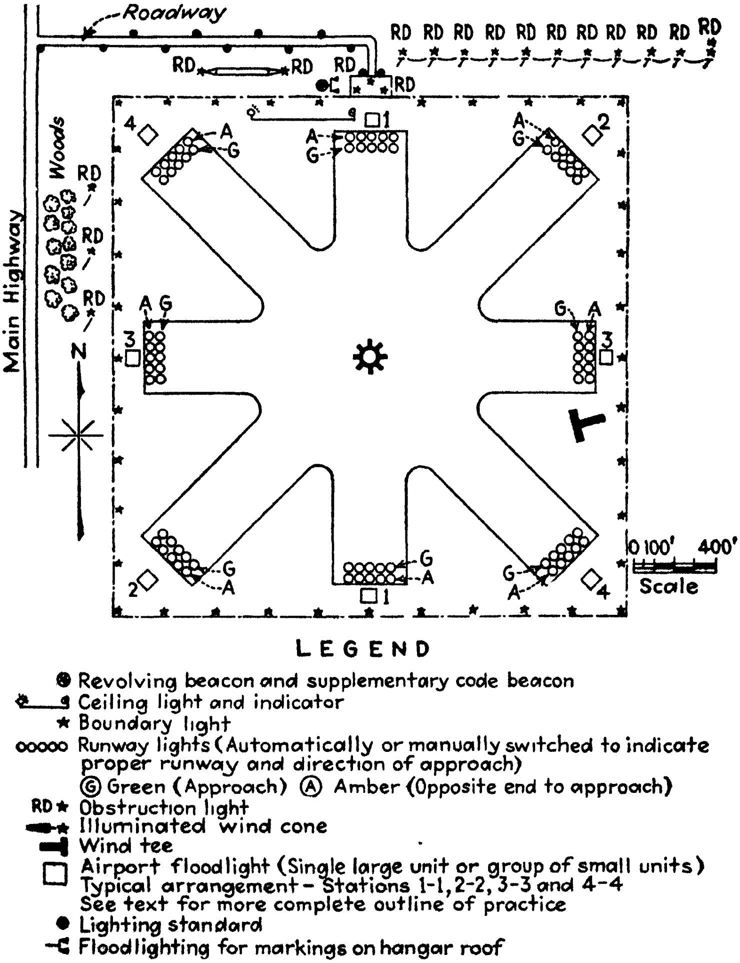
Boundary lights show the entire area available for landing so that the pilot in the air may know the shape and extent of the landing field. The lamp and receptacle are mounted in a weatherproof housing with an outer globe either clear or amber in color. The unit is placed about 3 ft. above the ground. The spacing should not be greater than 250 to 300 ft. and closer on an irregularly shaped field.

Red lights are used to mark obstructions to navigation and in the boundary lights to indicate soft ground, etc.

Green lights are placed at the ends of the principal runways.

Illuminated wind indicators indicate the direction of the wind at night. Since the wind cone is better for the take-off and the wind tee better for landing both should be used.

The wind cone may be satisfactorily illuminated by four 100-watt lamps in deep-bowl porcelain-enameled reflectors at sufficient distance above the cone to insure complete coverage.


Roadway
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RD
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Woods
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RD
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Main Highway
N
4
2
3
3
2
4
1
1
A
G
Scale
0 100' 400'
LEGEND
● Revolving beacon and supplementary code beacon
Ceiling light and indicator
★ Boundary light
ooooo Runway lights (Automatically or manually switched to indicate proper runway and direction of approach)
Ⓖ Green (Approach) Ⓐ Amber (Opposite end to approach)
RD★ Obstruction light
Illuminated wind cone
Wind tee
☐ Airport floodlight (Single large unit or group of small units)
Typical arrangement - Stations 1-1, 2-2, 3-3 and 4-4
See text for more complete outline of practice
● Lighting standard
Floodlighting for markings on hangar roof

FIG. 14-17.—Typical airport showing locations of various pieces of night lighting equipment.

The wind tee is a T-shaped structure having a light frame. It is striped alternately chrome-yellow and black and lighted at night by outlining with 25-watt incandescent lamps, in green enclosing globes, spaced 6 to 12 in. Some wind tees are outlined by gas tubes preferably green in color.

Ceiling-height indicators (Fig. 14-18) are used to measure the height of clouds above the landing field. This information may be radioed to the pilot of the approaching plane. The projector on the left should be powerful enough to throw a concentrated beam of light on a cloud 1,500 to 2,000 ft. above the ground. Its usual form is a 12 to 18 in. in diameter precision-grade glass parabolic reflector with a 250- to 1,000-watt lamp.

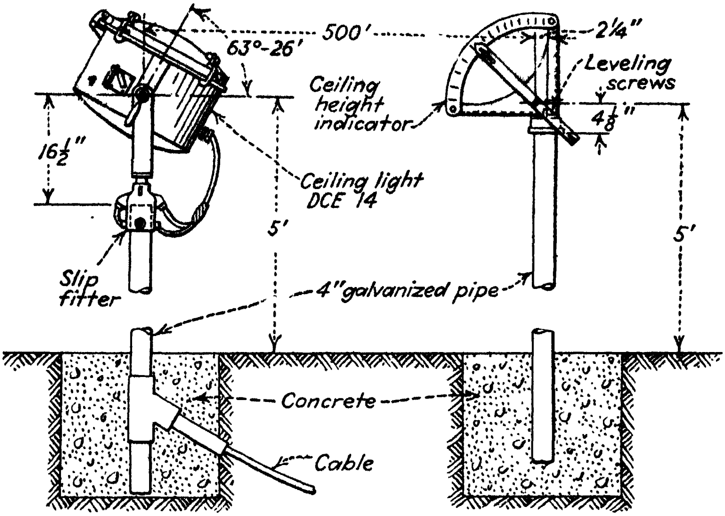

FIG. 14-18.—Method of installing ceiling projector and ceiling-height indicator for reading height of ceiling in feet.

Circular louvers cutting out all spill light should be used. The projector is directed upward at a definite angle. The height of the cloud in feet is read directly by the indicator or alidade located at a definite distance from the projector and near the landing-field office.

The landing field may be lighted in several ways. It is essential that the lighting units be placed comparatively low, produce minimum glare since glare might produce temporary blindness with disastrous results, and be practically immune to interruption.

If a single unit floodlight be used it should be equipped with an automatic lamp changer to bring a new lamp into focal position in case of lamp failure

Floodlights with lenses for spreading out the light over the field and louvers for intercepting the horizontal and upward light appear to be satisfactory.

One type of large field floodlight consists of six reflectors, 36 in. high and 15 in. wide, parabolic in vertical section and plain in horizontal section. The light source consists of eight 3,000-watt incandescent lamps. In front of each lamp is a spherical reflector which reflects the light that would otherwise be lost back through the focal point to the main reflectors thereby increasing the intensity of the main beam. The apparatus is mounted in a housing of structural steel with a glass front. Louvers are used here also to intercept the direct lamp light and upward stray light. The reflectors are adjustable so that the different beams of light may be directed as desired. The horizontal divergence of the combined beams is 160 deg. and the vertical divergence 6½ deg. Floodlights of this type are made having fewer lamps.

The advantage of the multi-lamp projector is that the burn-out of one lamp does not eliminate the unit.

The airport beacon which serves to guide the pilot to the airport may consist of a 24-in. crystal glass parabolic reflector of commercial accuracy and 10-in. focal length, and a 115-volt, 1,000-watt, 19,500-lumen lamp. The main beam receiving about 85 per cent of the light has a horizontal divergence of 5 deg. and a maximum apparent candle power of approximately 1,000,000. The beacon rotates at 6 r.p.m. showing a flash every 10 sec. of 0.1 sec. duration. The beam is visible 40 to 50 miles in clear weather and is aimed to reach the pilot 1,000 ft. above the adjacent beacons. About 15 per cent of the light is refracted upward, by prisms in the cover glass, to within 55 deg. of the zenith to guide the pilot when he is close to the beacon and out of the main beam.

Auxiliary code beacons, aviation green in color, usually accompany the airport beacon. These beacons, flashing in International Morse Code, serve to identify the airport and are particularly necessary when there are several airports in a city. The beacon code can be easily read by a pilot in the air.

Intermediate landing fields 30 to 50 miles apart are established on the federal airways so arranged as to serve in conjunction with the airports and other landing fields lying along the airways.

These are lighted, marked, and equipped similarly to the airports.

The standard airway beacon is a 36-in. rotating unit equipped with two doublet lens assemblies and a 110-volt, 1,000-watt aviation lamp with automatic lamp changer (Fig. 14-19). This unit throws a beam of 6-deg. divergence and 1,250,000 candle power in opposite directions. Each optical system consists of an inner prismatic lens which may be clear or colored and a clear outer prismatic lens. If the beacon rotates at 6 r.p.m. with a colored lens on one side it will show alternate flashes of colored and white light every 5 sec. If run at 3 r.p.m. with clear lenses it will give regular 10-sec. flashes of white light. This unit is a long-range beacon.

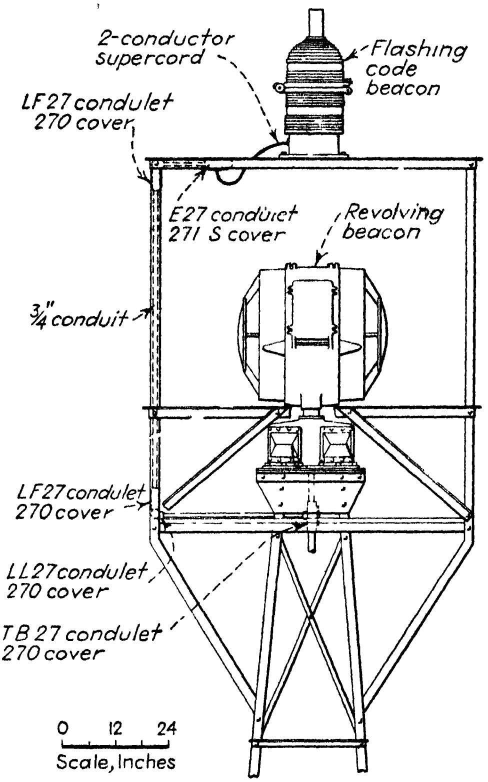

FIG. 14-19.—A 36-in. rotating beacon and auxiliary flashing code beacon installed on tower platform.

Two-course lights are mounted just above or below each revolving beacon, one pointing forward and one backward on the airway course. The course lights are 500-watt searchlight projectors fitted with special cylindrospherical mirrors and 18-in. doublet lenses, giving a beam of 15 deg. horizontal and 8 deg. vertical spread of 100,000-candle-power beam when fitted with aviation red or green lenses. Red doublet lenses are used at beacon-light sites along the airway and green lenses at intermediate landing fields. This color characteristic indicates to the pilot at long range the availability of landing fields. Each course light in turn flashes its code signal while the beam of the beacon is swinging through the other parts of the revolution. The code signals correspond to the mileage along the airway and run from 0 to 9. The pilot must know on which 100-mile section he is flying in order to identify his location.

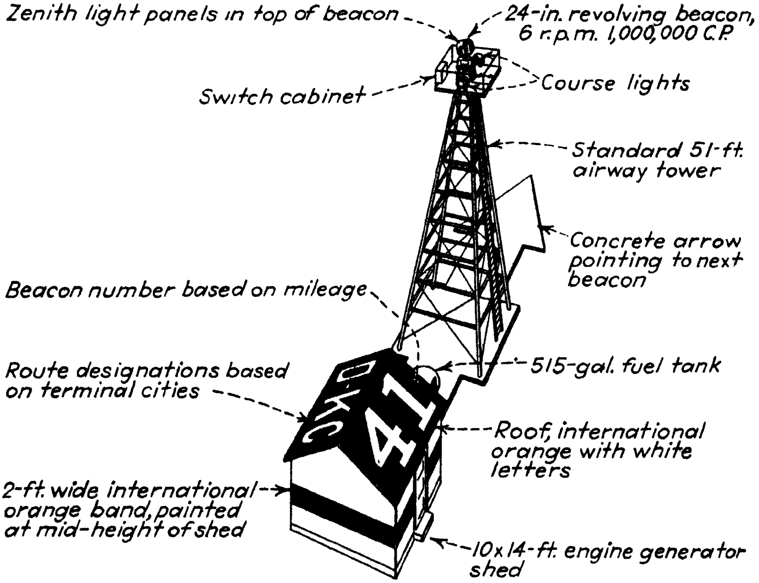
Zenith light panels in top of beacon
24-in. revolving beacon, 6 r.p.m. 1,000,000 C.P.
Switch cabinet
Course lights
Standard 51-ft. airway tower
Concrete arrow pointing to next beacon
Beacon number based on mileage
Route designations based on terminal cities
515-gal. fuel tank
Roof, international orange with white letters
2-ft. wide international orange band, painted at mid-height of shed
10x14-ft. engine generator shed
OKC
41

FIG. 14-20.—Detail of beacon-light installation with a 54-ft. concrete directional arrow.

The beacon and course lights are mounted on steel towers of standard construction and 50 to 90 ft. in height. For the convenience and safety of the airway mechanics a platform is provided below the lights (Fig. 14-20).

A directional arrow, 54 ft. in length, which points along the course to the next higher numbered beacon is located at the base of the tower. Small houses (10 by 14 ft.) when and where needed for storage of equipment or power house form the feather end of the arrow. The number of the beacon site is painted in large letters on the arrow or roof of the small house.

Beacon-light sites are chosen near highways and electric-power lines and also to secure the advantages of as high an elevation as practical so that intervening elevations will not obstruct the view from one beacon to the next. When intervening elevations obstruct this view auxiliary beacons or blinkers are usually used thereon so that light-to-light vision may always be maintained unless atmospheric conditions prevent.

The use of wind-driven electric generators makes it possible to install full automatic clock-controlled beacon lights on points of extreme inaccessibility. Such units require a small amount of lubricating oil and battery water but once in six months. Where smaller units are used to mark the airway the spacing is reduced to 3½ miles, thus offsetting the lower candle power and resulting in equal effectiveness. Acetylene is used for auxiliary lights or in lieu of standard beacon lights and course lights at standard spacings where electrical energy is not available.

For the guidance of airmen and the flying public, markers are placed on the roofs of buildings or on some suitable area giving the name of the city, indicating the direction of and distance to the landing field and its landing facilities. These are lighted at night.

Maps of the airways equipped with beacon lights and intermediate landing fields are available. Each map portrays an airway section and indicates the approximate locations of rotating and code-flashing beacons; airport and landmark light beacons; intermediate landing fields; commercial and municipal airports; and Army, Navy, or Marine Corps fields.

The airways are identified by the names of their terminal cities, reading from south to north and west to east. The code signals appearing on the maps beside the beacon light sites refer to the flashing characteristic of the course light beacons. These code flashes identify the number and location of the beacons.

Another series of maps show the locations of radio communication stations, radio range beacons, radio telephone-marker beacons, and landing range beacons, and give the name and frequency of each station. In addition, the maps indicate the call letters of communication stations, identifying signals of radio range beacons, characteristic signals of marker beacons, and the broadcasting schedules radio communication stations. Weather broadcasts from radio-communication stations approximately 200 miles apart along the airways keep the airmen advised of weather conditions.

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MACKALL, K. W.: "Airport Lighting," *Trans. Illum. Eng. Soc.*, vol. 27, p. 123, 1932; *Commission Internationale de l'éclairage*, p. 467.

PROBLEMS

1. Find the frequency of vibration of light in the region of the spectrum at which highest visible sensibility occurs.

2. Assuming the spherical reduction factor of the Hefner lamp to be 0.8 what should be its rating in mean spherical candle power?

3. If the lumens produced by a 100-watt lamp are 1,530 and its spherical reduction factor is 0.8 what are its mean spherical and its mean horizontal candle powers?

4. A spherical globe 18 in. in diameter and of good diffusing quality has an intensity of 4 candles per square inch. If the transmission coefficient of the globe is 0.80 and the spherical reduction factor of the type C lamp within is 0.85 what will be the mean horizontal candle power of the lamp?

5. A lamp having a mean spherical candle power of 500 is placed inside a light-density spherical globe. If the absorption of the globe is 15 per cent what is or should be its brightness in lamberts? Globe diameter 18 ins. Diameter of globe is 18 in.

6. The filament in a 500 watt tungsten lamp is 34 in. long and 0.0076 in. in diameter. The lamp produces 3,340 lumens. What is the average brightness of the filament in lamberts and in candles per square inch?

7. What are the candle power, lumens, lumens per watt, and life of a standard 110-volt, 150-watt tungsten lamp? What would be these values if the lamp operated on 115 volts?

8. The lumens output of a 100-watt lamp is 1,530 at 115 volts. What is its lumen output at 105 volts? at 125 volts? What should be the life of the lamp at each voltage?

9. A customer buys 100-watt, 110-volt Mazda lamps to use on a 115-volt circuit. If the lamps cost 20 cts. each and electrical energy 2 cts. per kilowatt-hour, does he save money or not and how much per lamp?

10. A customer buys 100-watt, 115-volt tungsten filament lamps to use on a 110-volt circuit. If the lamps cost 20 cts. each and electricity 2 cts. per kilowatt-hour how much more does this light cost him per million lumen hours than if 110-volt lamps were used?

11. A customer using 100-watt tungsten lamps found the average voltage to be only 90 per cent normal. Upon complaint the company raised the voltage to 105 per cent normal. The customer put 75-watt lamps in place of the 100-watt lamps. How many lumens per lamp and lumens per watt were obtained in each case? What relative electric-light bill resulted?

12. A 50-candle-power lamp is placed at the zero end of a 300-cm. photometer bar and a 25-candle-power lamp at the 300-cm. point. Calculate and plot curves for the illumination on each side of the photometer screen for 10 points along the bar. Indicate where the photometric setting should be.

13. A 25-candle-power lamp and a 50-candle-power lamp are placed at the ends of a photometer bar 300 cm. apart. How far from the 25-candle-power lamp is the screen when a photometric balance is obtained and what is its foot-candle illumination?

14. A 100-watt standard tungsten lamp produces twice the illumination on a normal surface as a 200-watt lamp of the same type. What are the relative distances of the lamps from the surface? What are the relative distances which will produce the same illumination?

15. A 50-candle-power and a 25-candle-power lamp are placed on the same side of a photometer screen at 100 cm. and 50 cm., respectively, from the screen. How far from the screen on the other side must a 100-candle-power lamp be placed to produce a photometric balance? What is the illumination on the screen in foot-candles?

16. A 50-candle-power lamp is placed at the 0 point of a 3-m. photometer bar and a 25-candle-power lamp is placed at the 200-cm. point. Locate two points along a line through the two lamps where the illumination on a normal screen will be the same due to each lamp.

17. A 300-cm. photometer bar is to be marked to read directly in candle power when a 25-candle-power comparison lamp is used and placed at the zero end. Compute the values to be placed at the 125-, 150-, and 225-cm. settings.

18. The readings on a standard photometer are 100 cm. on the side of the 20-candle-power standard lamp and 200 cm. between the photometer head and the test lamp. A sectored disk with one-third of its surface removed revolves in line with the test lamp. What is the candle power of the test lamp?

19. Absorbing screens having a transmission coefficient of 0.1 and 0.01 are used in the Sharp-Millar photometer. The apparatus was calibrated to read foot-candles with the screens not in use. If the position of the screens is not known and the setting indicates 20 foot-candles what may be the value of the illumination?

20. Two lamps of 25 and 100 candle power, respectively, are placed at the ends of a 3-m. photometer bar. (*a*) What is the illumination on the photometer screen when a balance is secured? (*b*) What proportion of material should have been removed in a sector disk to be used with the above lamps to give highest accuracy in settings? (*c*) A piece of smoked glass is placed between the 100-candle-power lamp and the screen. The balance is now at 1.75 m. from the 25-candle-power lamp. What is the transmission constant for the filter?

21. An illumination survey showed an average illumination intensity of 4.5 foot-candles with 105 volts on the installation. What should be the illumination with normal voltage (110 volts) on the lamps?

22. A standardized 20-candle-power tungsten lamp was used to photometer another tungsten lamp. The results indicated 35 candle power for the latter. Upon calibrating the voltmeters it was found that the standard lamp was operating 1 per cent more than normal voltage and the test lamp 2 per cent under normal voltage. What should be the correct candle power of the test lamp?

23. A 250-candle-power street lamp is on the same level with a second-story window. The light passes through the glass to a silvered-glass mirror 100 ft. from the lamp. It is reflected specularly to a wall 10 ft. away. What normal incident illumination would be expected on the wall?

24. A lamp is placed 10 ft. above the floor and 6 ft. from a wall. What is the illumination E_v at a point on the wall 4 ft. above the floor and 4 ft. to the left of a vertical plane passing through the lamp and normal to the wall, the candle power in the direction of the point being 200 candle power?

25. A lighting unit produces 100 candle power in all directions in the lower hemisphere. Determine the lumens emitted in the 0.- to 15-deg zone and in the 75-to 90-deg. zone.

26. Assume a light source giving 200 candle power in all directions in the lower hemisphere. If a reflector redirects half of the light flux from the 70- to 90-deg. zone into the 0- to 20-deg. zone what will be the average candle power in the latter zone?

27. The light flux emitted through the 0- to 2-deg., 44- to 46-deg. and the 89- to 91-deg. zones is the same for each—20 lumens. Calculate the relative areas of the zones and the respective average candle-power values in the three zones.

28. If 60 per cent of the light from a lamp of 500 mean spherical candle power be gathered into a 15-deg floodlight beam what should be the intensity of the beam and the incident illumination on a building 200 ft. distant?

29. If 40 per cent of the light from a lamp emitting 50 mean spherical candle power be concentrated into a 2-deg. searchlight beam, what should be the intensity of the beam and the incident illumination on an object ¼ mile away?

30. A 160-amp., 60-volt searchlight arc produces 110,000 lumens. If 30 per cent of this light flux can be concentrated into a 2-deg. beam (*a*) what should be the average candle-power intensity of the beam? (*b*) What should be the foot-candle illumination on a normal surface ½ mile away?

31. On a piece of tracing cloth or translucent paper reproduce Fig. 7-7 and determine the mean spherical and mean lower hemispherical candle powers and lumens for Fig. 7-8 or some other assigned by the instructor.

32. On a piece of tracing cloth or translucent paper reproduce Fig. 7-10 and determine the mean spherical and mean lower hemispherical candle powers and lumens for Fig. 7-8 or some other assigned by the instructor.

33. Check the results obtained in the two preceding problems by marking off the mid-zone distances from the vertical on the edge of a sheet of paper as explained in the text under Wohlauer's method.

34. With local prices of 100-watt lamps and kilowatt-hours, what is the relative cost of operating 110- and 120-volt lamps on the local 115-volt circuit?

35. A 200-watt 115-volt lamp costs 40 cts. What is the cost of light per megalumen-hour with electricity at 3 cts. per kilowatt-hour? (*a*) If operating at normal voltage? (*b*) When operating at 95 per cent voltage? (*c*) Lumen-hours per dollar for (*a*) and (*b*)?

36. In lighting a factory assume: one 100-watt lamp to each operator; the lamp is used 2 hours per day, 300 days per year; the life of the lamp is 1,000 hr.; and the operator works 8 hr. per day, 300 days per year.

Cost of lamp	$0.20
Cost of reflector	2.50
Cost of wiring per outlet	8.00
Cost of cleaning per lamp twice a month	0.03
Cost of energy per kilowatt-hour	0.02
Cost of labor per hour	0.45
Interest on investment	8 per cent
Depreciation on reflector and wiring	12½ per cent

Find (*a*) the cost of producing illumination per man per year; (*b*) the cost of labor per man per year; (*c*) the number of minutes per day of the man's labor equal to the cost of illumination.

37. If the illumination on a normal surface due to a full moon is 0.03 foot-candle what is the candle power of the moon? How far from the surface should a standard candle be placed to produce the same illumination? How do you explain the difference between this value and that given in Chap. III?

38. If the intensity of illumination due to the sun is 10,000 foot-candles near noon on a summer's day, what is the candle power of the sun at that time? What is the reason for the difference of this value and that given in Chap. III?

39. The polar curve of a light source is a circle and the light all emitted in the lower hemisphere. The maximum or 0-deg. value is 500 candle power. The unit is placed 10 ft. above the working plane and 10 ft. from one side wall.

a. Calculate the illumination E_h on the working plane at 2-ft. steps from beneath the source. Neglect reflected light.

b. Calculate the illumination E_v on the vertical plane at 2-ft. steps from the level of the lamp to the floor.

40. The horizontal illumination at a point due to a light source is E_h and the vertical illumination due to the same source is E_v. Is the normal illumination at the point equal to $\sqrt{E_h^2 + E_v^2}$? What is meant by horizontal and vertical illumination?

41. If the illumination from an assumed point source of light is uniform over a certain area of the working plane prove that the illumination will also be uniform over a similar part of any plane parallel to the working plane. What are the relative areas of the uniformly illuminated parts of the different planes and what are the relative values of the illuminations?

42. The illumination on the page of a book is 10 foot-candles when held normal to the light rays. What is the illumination intensity if the book is turned 30 deg.? If turned 45 deg.?

43. A living room 16 by 20 ft. having a light ceiling and medium-colored walls is lighted by a 200-watt type C lamp in a mirrored, indirect luminaire. What should be the average foot-candle intensity of illumination?

44. Specify the location and size of lamps for lighting a store 40 ft. wide and 100 ft. deep, having fairly light ceilings and medium walls. The one-piece opal unit with a flattened reflecting top was adopted for the installation. Assume an illumination of 8 foot-candles.

45. Choose the lighting system and locate the units for lighting a general office 60 by 100 ft. with a ceiling 16 ft. above the floor. The ceiling is white. The walls consist of 50 per cent glass, the remainder being fairly dark. Determine the number and size of type C lamps to give the necessary illumination for accurate office work.

46. The indoor field of the University of Maine armory-gymnasium is 304 by 170 ft. The roof along the center is 67 ft. above the ground. Along the sides it is 30 ft. high. It is of the arch style. Design a lighting installation that will meet the requirements for baseball practice.

47. A room 15 by 20 ft. is lighted by two 100-watt lamps. If the average foot-candle intensity is 6, what is the utility factor of the lighting unit?

48. An office manager wishes you to give him the details of a lighting installation for his office. The room is 40 by 50 ft.; ceiling 18 ft. above the floor, and white; walls, one-third glass and two-thirds white. Specify:

a. Number and size of lamps.

b. Type of luminaire.

c. Location and height of luminaire.

d. Explain your calculations and reasons for your decisions.

49. A street lamp is placed 30 ft. above the street. At a point 50 ft. from beneath the lamp the illumination E_n measured on a test plate placed normal to the rays is 0.5 foot-candle.

a. What is the horizontal illumination E_h at this point?

b. What is the illumination at this point on a vertical surface E_v?

c. What is the candle power of the source in this direction and what is its angle (from the vertical) on the polar curve?

50. The normal illumination on a marble out in a street due to a street lamp is 0.2 foot-candle. The lamp is 20 ft. above the street and 30 ft. horizontally from the marble.

a. What is the candle power of the lamp in the direction of the marble?

b. What is the illumination on the top of the marble?

c. What is the illumination on the side of the marble toward the lamp?

51. A street is lighted by lamps giving candle power and distribution indicated by curve *c*, Fig. 14-6. If these lamps are placed 100 ft. apart and on opposite sides of a street 40 ft. wide, what will be the horizontal illumination (height of lamp 20 ft.):

a. In center of street between opposite lamps?

b. In center of street equidistant from four lamps?

c. Halfway between lamps along the curb?

d. One-fourth the way between lamps along the curb?

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